Water Resources Report Number 49
MISSOURI STATE WATER PLAN SERIES
VOLUME V

Hydrologic Extremes in Missouri: Flood and Drought

MISSOURI DEPARTMENT OF NATURAL RESOURCES
Division of Geology and Land Survey

Front cover: The Missouri River near Jefferson City, Missouri during the 1993 flood. Photo by Nick Decker, DNR.

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Hydrologic Extremes in Missouri: Flood and Drought

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PREFACE

MISSOURI STATE WATER PLAN TECHNICAL VOLUME SERIES

The Missouri Department of Natural Resources State Water Plan Technical Volume Series is part of a comprehensive state water resource plan. This portion is designed to provide basic scientific and background information on the water resources of the state. The information in these technical volumes will provide a firm foundation for addressing present and future water resource needs and issues. Each volume in the series deals with a specific water resource component.

Volume I

The ***Surface Water Resources of Missouri*** contains a basin-by-basin assessment of Missouri's surface water resources. It discusses the effects of climate, geology and other factors on the hydrologic characteristics of major lakes, streams and rivers. It also assesses surface-water availability and development in the state.

Volume II

The ***Groundwater Resources of Missouri*** presents information on the availability and natural quality of groundwater throughout the state. It focuses on Missouri's seven groundwater provinces and includes their geology, hydrogeology, areal extent, general water quality, and potential for contamination. Aquifer storage estimates are given for each aquifer and county. The report also reviews the different types of water-supply wells in use and how water well construction techniques vary between areas and aquifers.

Volume III

Missouri Water Quality Assessment focuses on the current quality of Missouri surface water and ground-water. The volume looks at chemical, bacteriological and radiological water-quality, and natural and man-induced water-quality changes.

Volume IV

The ***Water Use of Missouri*** describes how Missouri is presently using its surface-water and groundwater resources. The report covers private and public water supplies, industrial and agricultural water uses, and water use for electrical power production, navigation, recreation, fish and wildlife.

Volume V

Hydrologic Extremes in Missouri: Flood and Drought provides basic information about flood and drought specific to Missouri. A historical perspective is given, as well as information that can be used in planning for hydrologic extremes. It also describes concepts and defines terminology helpful in understanding flood and drought.

Volume VI

Water Resource Sharing - The Realities of Interstate Rivers presents Missouri's views concerning interstate rivers. Because of its location, Missouri can be greatly affected by activities and water policy in the upper basin states of the Missouri and Mississippi river basins. Missouri policy can also affect downstream states on the Mississippi, Arkansas and White rivers. Many serious issues affecting these rivers have less to do with their physical characteristics than with political, economic and social trends.

Volume VII

Missouri Water Law provides an overview of the laws that affect the protection and use of Missouri's water resources. It supplies reference information about existing doctrines, statutes and case law.

EXECUTIVE SUMMARY

Improving our understanding of flood and drought is a very important step toward preparing for these hydrological extremes, and for reducing many of their negative impacts. This volume of the State Water Plan serves as a basic informational tool for understanding hydrologic extremes in Missouri. It provides an overview of hydrologic concepts and discusses historical and scientific accounts of flood and drought in the state.

There are several types of flooding: **Flash flooding** occurs rapidly and violently. **Flooding on streams and rivers** may affect large areas, develop over a period of days, and last for months. **Ponded flooding** does not carry the force of moving water.

The nature of these flood types is quite different, and the steps taken to reduce their damages should also be different. For example, considerations for building location and construction methods in an area prone to ponded flooding would not be the same as those needed in an area that is prone to flash flooding.

There are also several types of drought. **Meteorological drought** is characterized by a lack of precipitation. **Hydrologic drought** is characterized by declining streamflow, lake levels and groundwater. **Agricultural drought** is characterized by an inadequate amount of soil moisture needed to sustain healthy crops. **Socioeconomic drought** is characterized by an insufficient amount of water being available to meet the social or economic demand for it. Although there is much overlap among these types of drought, they offer different perspectives.

Going a couple weeks without rain could be devastating to someone dependent on rain for growing crops, whereas a municipal water supply facility probably would not be affected by such a short agricultural drought period.

Floods and droughts are normal climatic events and help shape the physical and biological features of our aquatic systems. Like other natural phenomenon, they can have severe impacts. In planning for floods and droughts, it is important to recognize the interaction betwee hydrologic, sociologic, economic and environmental factors. The drought that occurred in the 1930s during the Great Depression illustrates this point. Historic accounts tell us there were severe social and economic impacts during the 1930s even though the Palmer Drought Severity Index does not indicate that this period was that extreme. The impacts felt during the 1930s were probably magnified by the interactions between the duration of the event, the economy, low rainfall, high temperatures, and insect infestations. Factors such as land-use, shifting channels, flood control structures, water supply structures, and demand for water affect the severity of floods or droughts.

Historic and scientific accounts demonstrate that floods and droughts have occurred many times throughout recorded history and will continue to do so in the future. This can be seen in news paper clippings, the cyclic patterns of the Palmer Drought Severity Index, and through the interpretation of narrow and wide bands in tree rings that record centuries of climate variations. The flood of 1993 was a

record setting event that reached the 100-500 year recurrence level at some locations. We have to go back in history to 1844 to find a flood that rivaled the 1993 flood in magnitude at some of the same locations. But just because these events were about 150 years apart, does not mean that a similar large event is not likely to occur again at any time soon. In fact, the 1995 flood was almost as large as the 1993 flood at many locations.

Several important needs were identified in the development of this volume and include:

(1) A great need for the development of basic climatic and hydrological databases. There are only six existing evaporation stations in Missouri; climatic region five (Southeast) does not have any stations. Streamflow data are not available in many areas that have drought or flood problems.

(2) Maps and studies are needed. Maps of rainfall, evaporation, runoff and streamflow are needed, especially those related to hydrologic extremes. Better methods are needed for estimating streamflow for areas that have no streamflow stations.

(3) Information on extreme events is deficient. All too often the only information available are long-term averages such as average annual rainfall or streamflow. More databases and products should be developed for hydrologic extreme analysis, which are needed for many purposes such as irrigation management, in-sream flow requirements, and municipal water system design.

(4) Drought indices for different regions of the state, which have different characteristics, are needed. We also need better indices for different applications or types of drought, such as agricultural or water supply.

(5) Objective drought definitions and explicit information about what factors trigger different types of droughts are needed. The lack of this information has been a key obstacle to better understanding, managing and responding to drought. Without clear drought definitions, it is difficult to evaluate the effectiveness of drought response activities.

(6) Flood and drought programs should emphasize not only emergency or short-term responses, but also long-term planning. The objective of these activities should focus on the reduction of society's vulnerability to future floods and droughts.

INTRODUCTION

Floods and droughts are at the two poles of hydrologic extremes. They are among the most costly natural disasters in the United States and other parts of the world in terms of their impacts on human activities and economic losses.

Floods are relatively easy to characterize. They are usually local, and occur over a relatively short duration, typically a few hours to a few days. But on Missouri's large rivers, floods can last for months. The impacts of flooding can be seen by the damage done to things in its path. It has been reported that 90 percent of the damages related to natural disasters (not including droughts) are caused by floods.

Droughts, on the other hand, are somewhat elusive. It is hard to pinpoint the onset of drought. Droughts are long-term phenomena that can last an extended period and are usually associated with a water deficit that has accumulated over a few months to a few years. Droughts affect large areas, sometimes covering much of the nation. It is difficult to identify the impacts because they are spread over time and not limited to a finite area such as in a flood plain. However, the physical, social and economic impacts of drought can be significant and long-lasting.

As a normal climatic feature, floods and droughts are inevitable. However, proper planning and management of water resources can certainly reduce their impacts and the societal vulnerability to such events.

Droughts and floods are closely related to climate. Throughout this report there are references to Missouri's six climatic regions: the Northwest Prairie is Region 1, the Northeast Prairie is Region 2, the West Central Plains is Region 3, the West Ozarks is Region 4, the East Ozarks is Region 5, and the Bootheel is Region 6. Illustration 1 shows the location of these six climatic regions.

According to Steve Hu, Ph.D., Missouri State Climatologist, boundaries of these regions were developed by his predecessors, Jim McQuigg, Ph.D., and Wayne Decker, Ph.D., based on landscape and climatological factors.

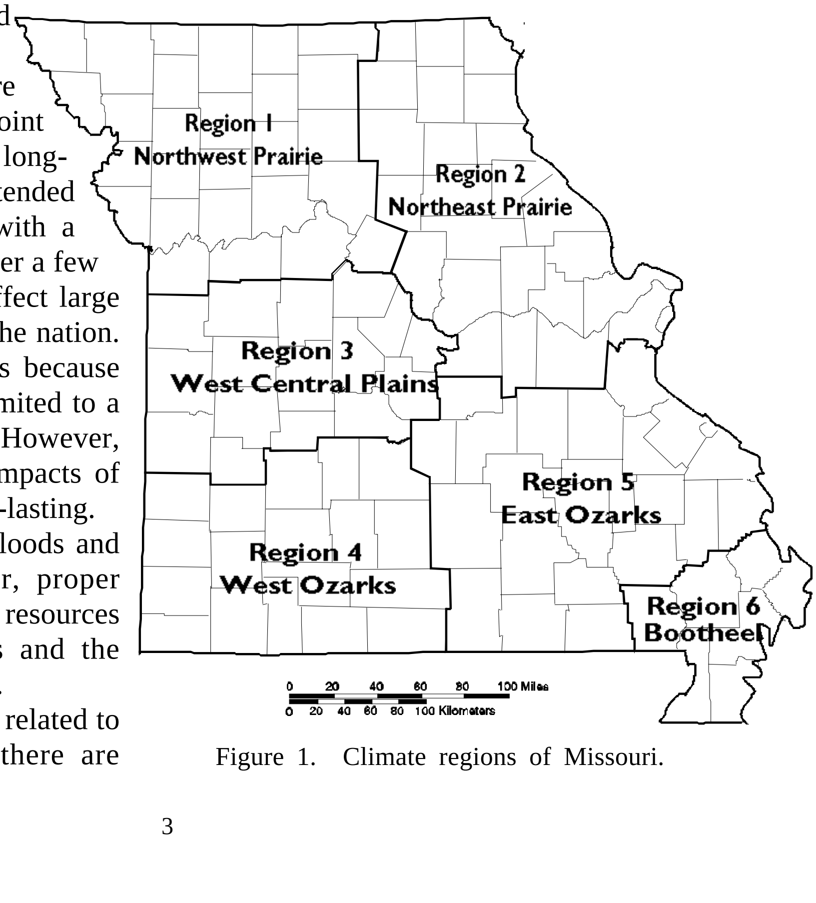

Figure 1. Climate regions of Missouri.

ACKNOWLEDGMENTS

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We would like to acknowledge the following people who provided input to the contents: Steve McIntosh, DNR/DGLS; Steve Hu, Department of Soil and Atmospheric Sciences, University of Missouri—Columbia; Charlie DuCharme, DNR/DGLS; and Todd Miller, DNR/DGLS. Todd Miller also provided assistance with illustrations of the report.

We would also like to express our appreciation to Susan Dunn, DNR/DGLS, for preparing illustrations and the overall layout of this report, and Dwight Weaver, DNR/DGLS, for editing the manuscript and coordinating the printing.

FLOOD

INTRODUCTION

Flooding is generally defined as the condition when water leaves the banks of the river. It is usually the direct result of rainfall, but can be caused by snow melt, dam failure, or reservoir releases (primarily done to free up flood storage in a reservoir, or for positive environmental effects).

Floods have been a problem in Missouri throughout history, with memorable events like the flood of 1844 on the Mississippi River or the recent 1993 flood in the Missouri and Upper Mississippi River basins.

RAINFALL

Floods are usually the direct result of rainfall. The primary physical aspects of storms that are of interest concerning flooding are the intensity, duration and the extent of the land area covered (areal) by precipitation.

Changnon and Vogel (1981) recognized intense localized storms that are common in the Midwest. They estimated that 40 of these storms occur in Illinois each year. The storms usually last from 3 to 12 hours, are generally limited to less than 400 square miles, and have 1- to 4-hour rainfall totals in excess of 3 inches. Huff (1986) identified larger storms which occur about once every two years in the Midwest. These storms generally last from 12 to 24 hours, cover an area of 2,000 to 5,000 square miles, and produce 10 to 12 inches of rain at the storm center.

Rainfall statistics have been developed for different durations and areal extent. The most common source of this information has been the U.S. Weather Bureau, Technical Paper 40 (TP40) from 1961.

A more recent source of rainfall information is the *Rainfall Frequency Atlas of the Midwest* by Floyd A. Huff and James R. Angel, Illinois State Water Survey, Champaign, Bulletin 71, 1992. Figures 2 through 7 show rainfall amounts for various durations and return periods for the climatic regions of the state.

The 30 minute precipitation event with a 10-year return period varies from 1.72 inches in the Northeast Region to 2.05 inches in the Southwest Region. In contrast, the 100-year storm for the 30 minute duration is about an inch higher, varying from 2.67 inches in the Northeast Region to 3.03 inches in the Southwest Region. As can be seen in the charts, rainfall amounts increase at a fairly high rate as rainfall duration increases from 30 minutes to about 6 hours. It then tapers off relative to time (the rate decreases; i.e., inches per hour).

FLOOD HYDROGRAPH

In flooding, we are normally concerned with streamflow that results from rainfall. A graph which plots flow versus time is called a hydrograph. Figure 8 shows a typical storm hydrograph. The basic components of the hydrograph are peak, rising and falling limbs, basin lag time, and volume. The peak is the maximum flow rate that occurred. The slope, or steepness, of the rising and falling limbs indicate the rate at which flow increases or diminishes. The lag time is the difference

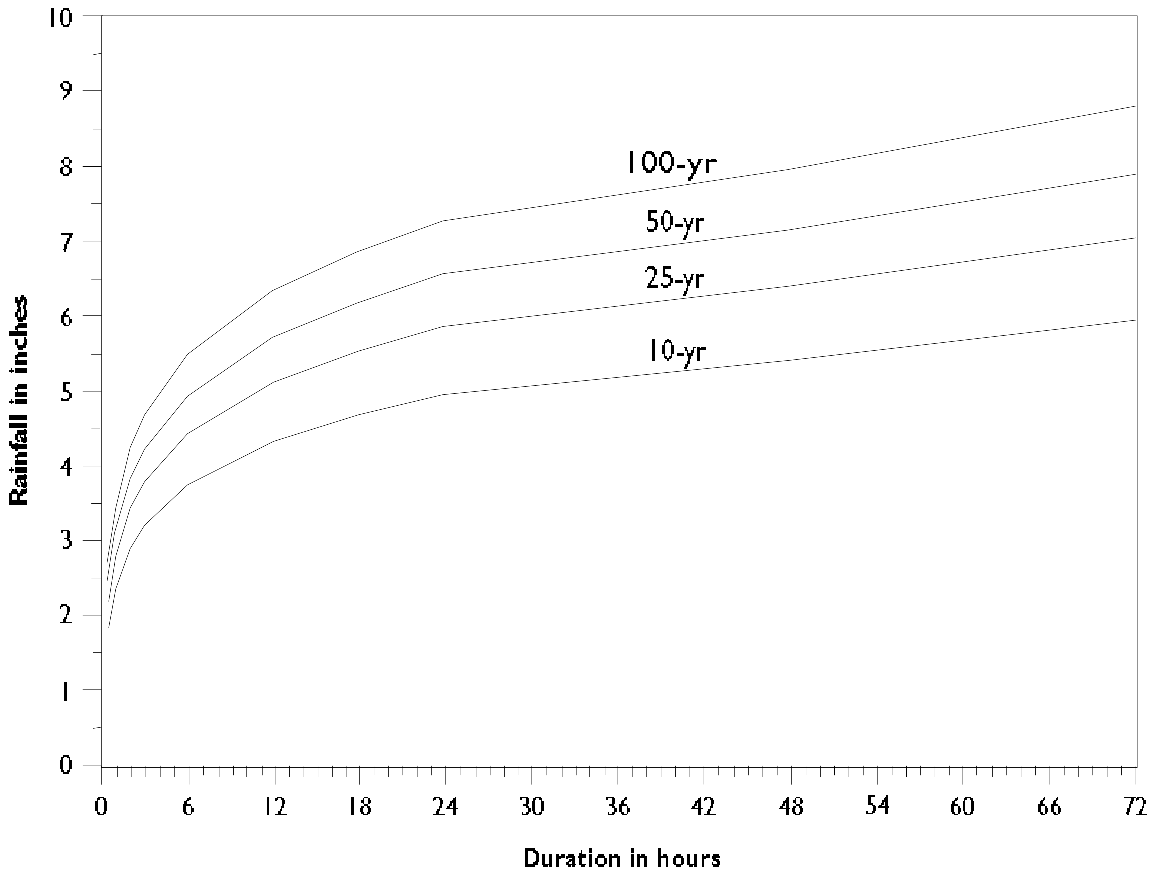
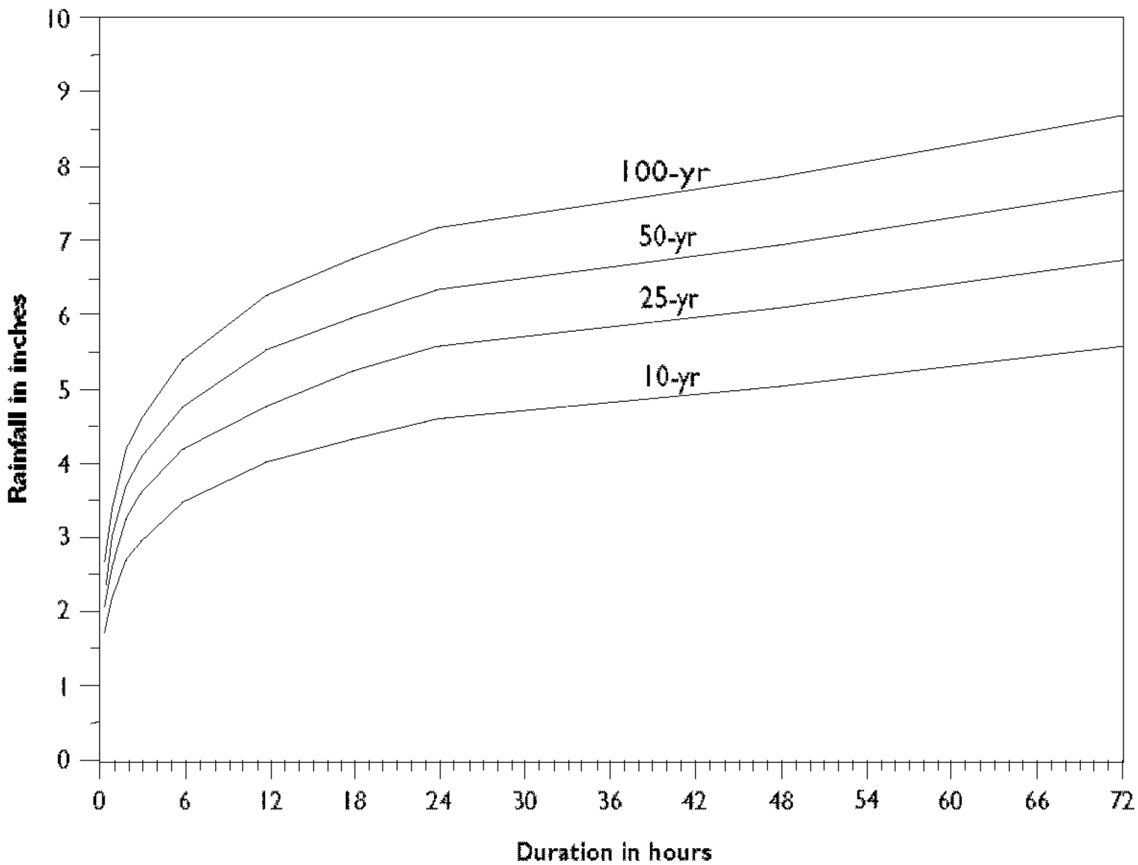


Figure 2. Rainfall accumulation for durations of 0.5 to 72 hours at recurrence intervals of 10 to 100 years in Region 1 (Northwest Prairie). Data source: Huff and Angel, 1992.



100-yr
50-yr
25-yr
10-yr
Rainfall in inches
Duration in hours
0
1
2
3
4
5
6
7
8
9
10
0
6
12
18
24
30
36
42
48
54
60
66
72

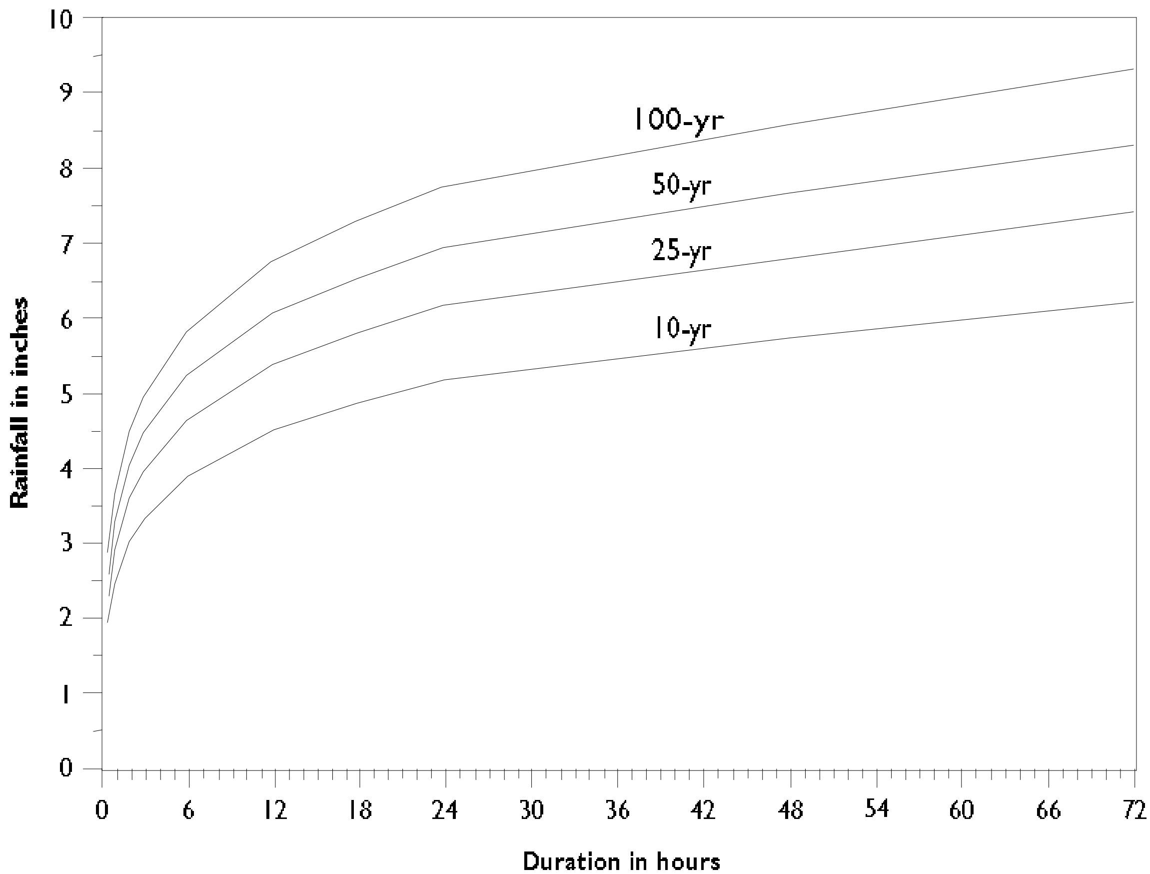


Figure 4. Rainfall accumulation for durations of 0.5 to 72 hours at recurrence intervals of 10 to 100 years in Region 3 (West Central Plains). Data source: Huff and Angel, 1992.

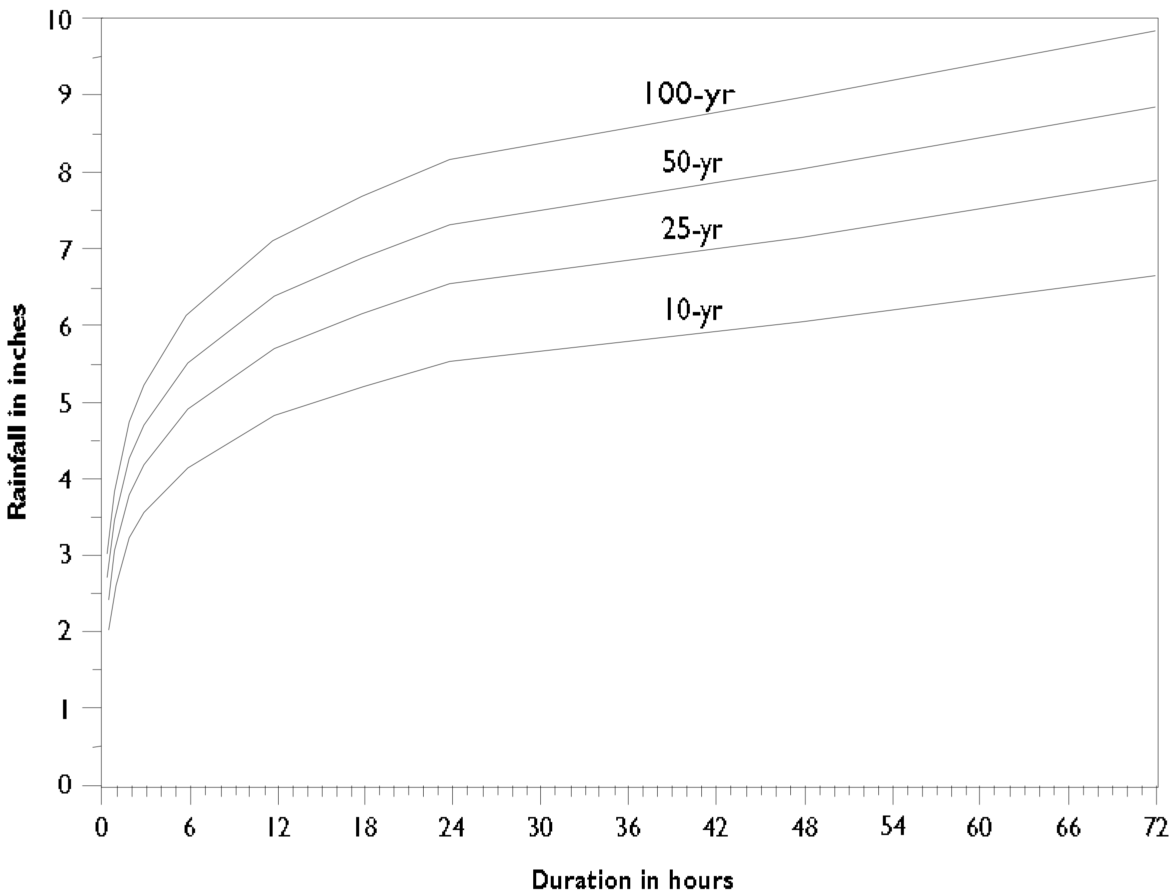


Figure 5. Rainfall accumulation for durations of 0.5 to 72 hours at recurrence intervals of 10 to 100 years in Region 4 (West Ozarks). Data source: Huff and Angel, 1992.

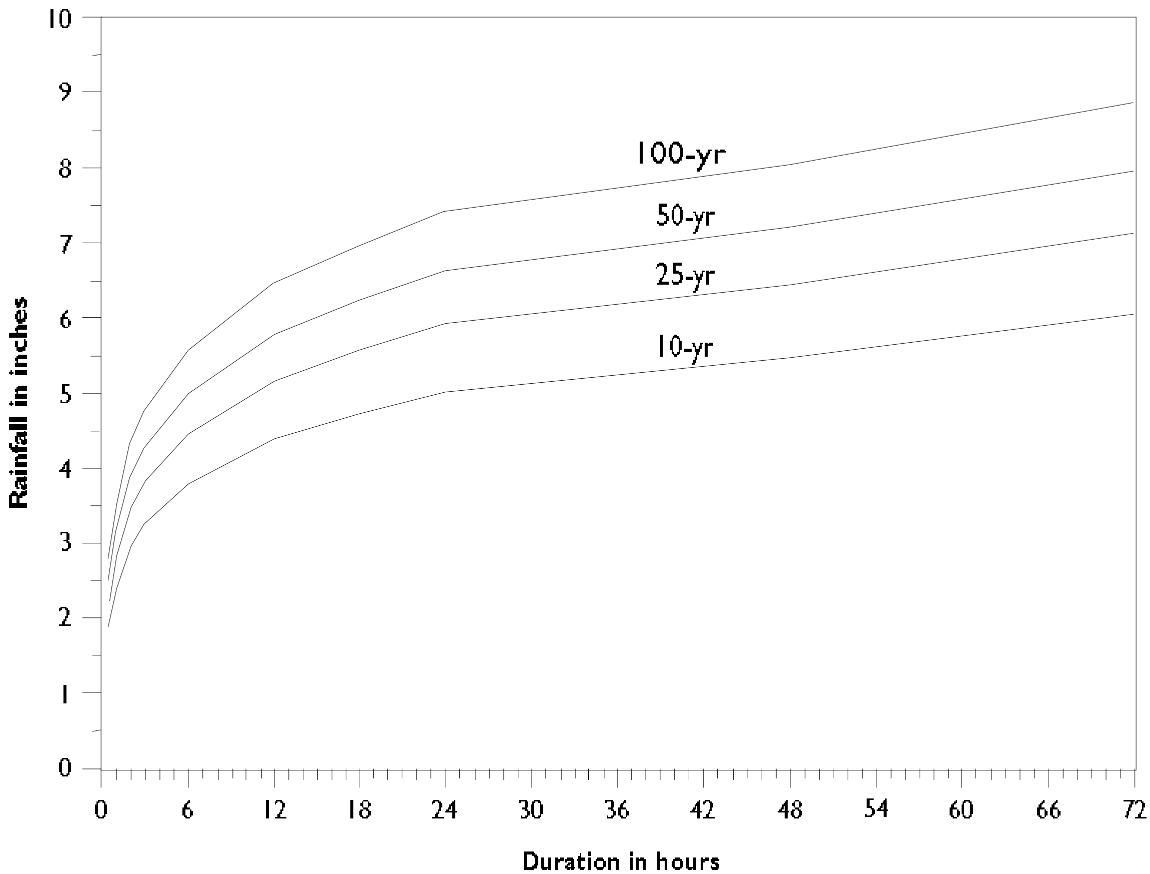


Figure 6. Rainfall accumulation for durations of 0.5 to 72 hours at recurrence intervals of 10 to 100 years in Region 5 (East Ozarks). Data source: Huff and Angel, 1992.

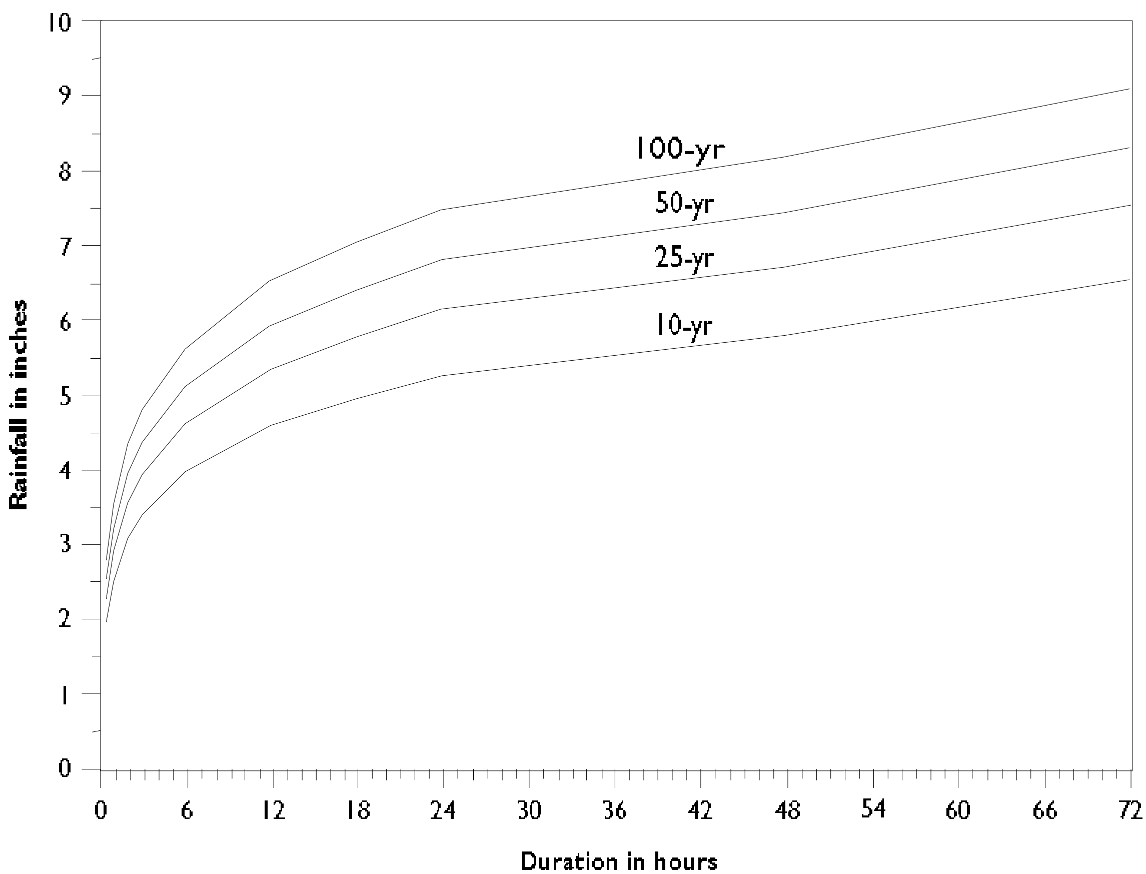


Figure 7. Rainfall accumulation for durations of 0.5 to 72 hours at recurrence intervals of 10 to 100 years in Region 6 (Bootheel). Data source: Huff and Angel, 1992.

between the centroid of excess rainfall (runoff) and the centroid of the hydrograph; showing us the temporal relationship between rainfall, runoff and streamflow. A shorter lag time means quicker response to a storm and less delay to the peak than a longer lag time. The volume is the summation of flow over time (the area under the curve).

There are many factors that influence the shape of a hydrograph. Some of these are physical characteristics of a watershed that do not normally change, such as the drainage area. Becker (1990) developed a set of equations that relate peak discharge to drainage area. Roughly, peak discharge increases at the rate of the drainage area to the power of 0.8 ($DA^{0.8}$).

Figure 9 demonstrates the effect that drainage area has on the hydrograph. Keeping all other factors except drainage area fixed, the lag time goes from about 1.5 hours to about 5 hours when the drainage area increases from 1 square mile to 33 square miles (the peak occurs much quicker with a smaller drainage area). In this same example, the peak discharge goes from about 730 cfs (cubic feet per second) to about 12,000 cfs. The watersheds with larger drainage areas have attenuated falling limbs; it is much longer before flood waters recede. This example demonstrates that floods in large watersheds have a much different character than floods in small watersheds. This should be taken into account in flood response and mitigation planning.

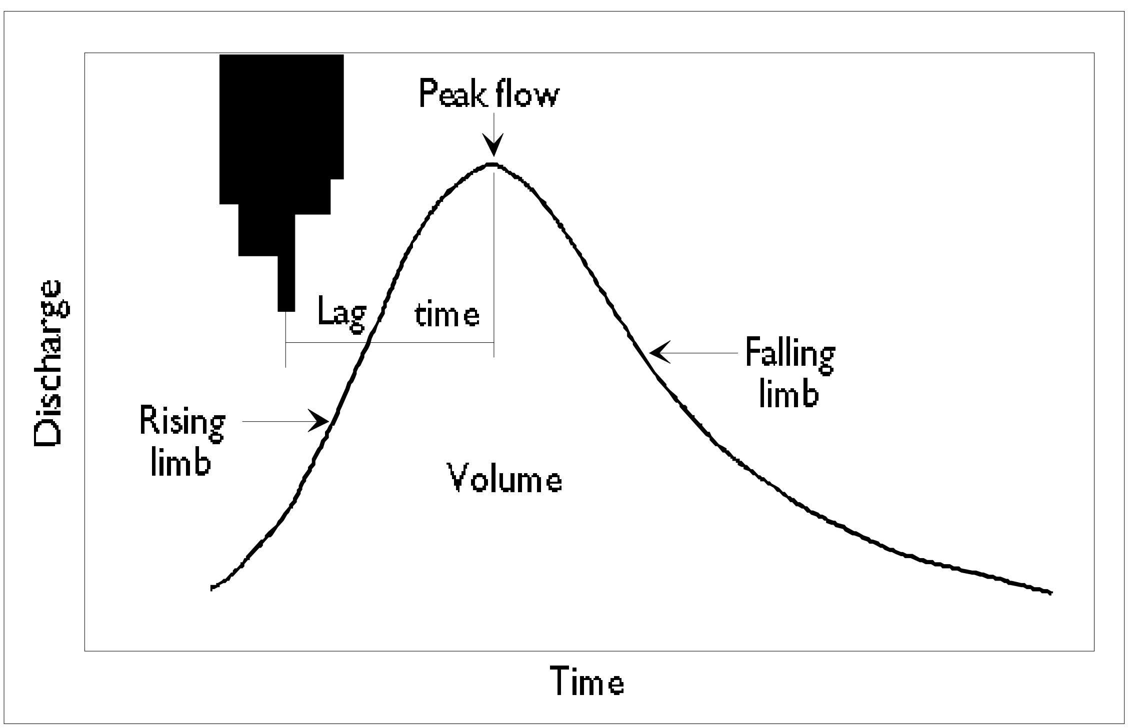


Figure 8. Components of a streamflow hydrograph.

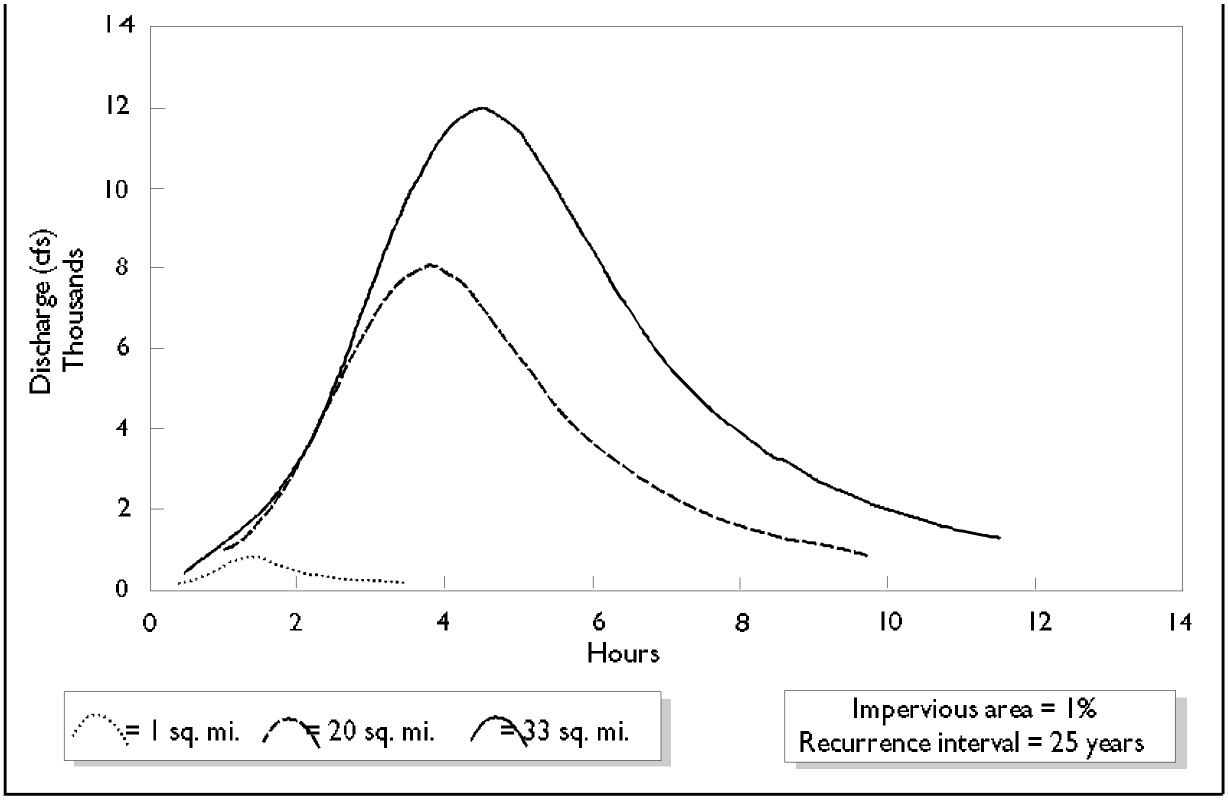


Figure 9. Hydrographs for watersheds with 1, 20, and 33 square mile drainage areas. Percent impervious area and storm magnitude are the same in the three watersheds.

One of the common ways that we alter the nature of floods is through urban development in a watershed. As development increases so does the impervious area (such as roofs and pavement). Becker (1990) found that peak discharge increased as a function of the percent of the impervious area to the power of about 0.14 ($I^{0.14}$). Using this relationship, Figure 10 demonstrates the affect of going from an undeveloped watershed, to partially developed, to a highly developed urban watershed (using some general estimates of impervious area associated with development). Note the dramatic effect that development can have on the hydrograph. Both the rising limb and the falling limb of the hydrograph are much steeper, the lag time is shorter, and peak discharge increases as development occurs; the peak is about twice as high and occurs in about half the time, when comparing the developed urban watershed with the undeveloped rural watershed.

To balance the impacts that development has on storm runoff, some areas use detention and retention basins. These are structures that are built to temporarily or permanently store water.

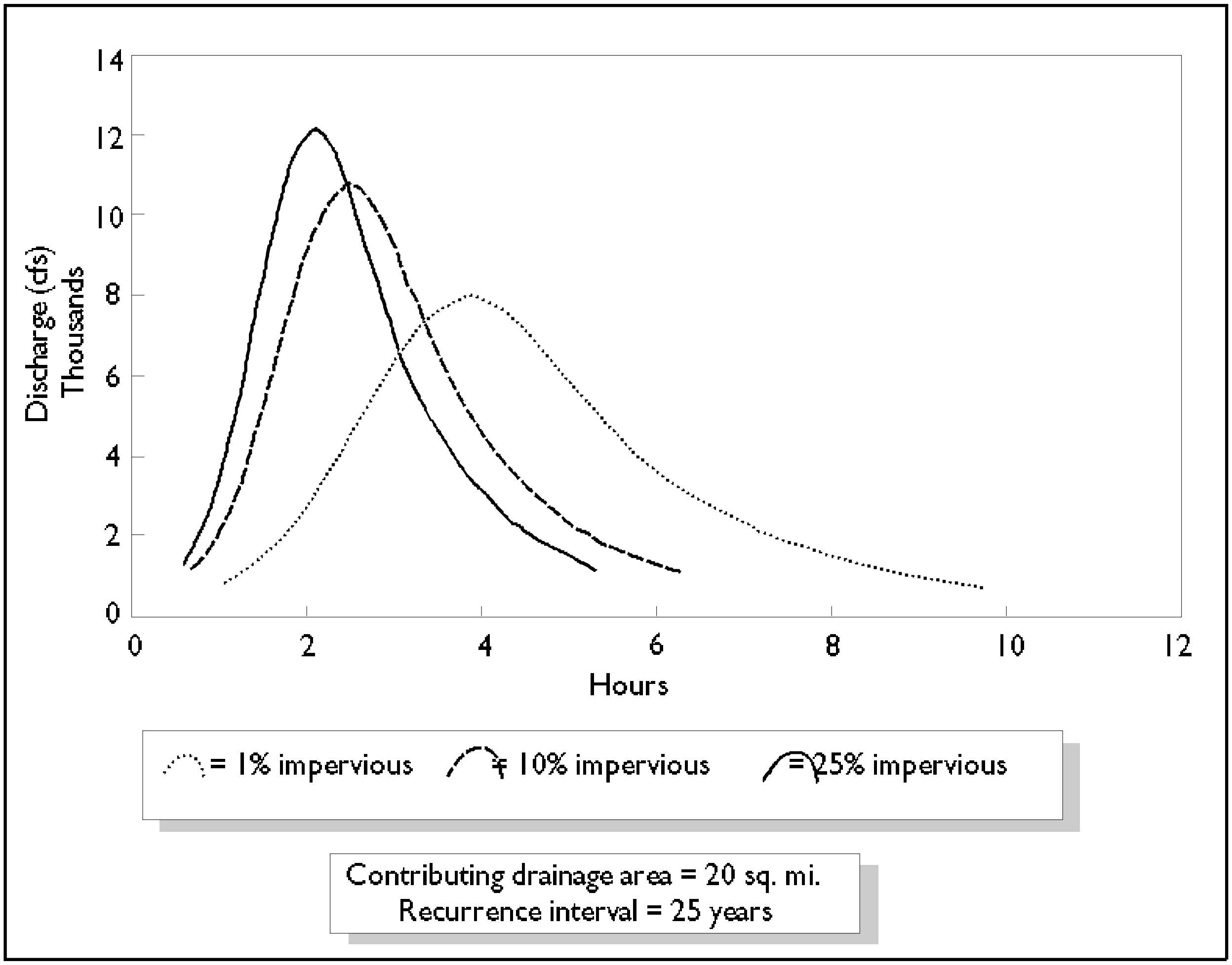


Figure 10. Hydrographs for watersheds with 1, 10, and 25 percent impervious area. Drainage area and storm magnitude are the same in the three watersheds.

STREAMFLOW

The U.S. Geological Survey (USGS) maintains a network of stream gages in Missouri. By using a float that is connected to the stream, the water surface elevation (stage) is recorded. Figure 11 shows an example of a gaging station. Stage is normally reported in feet above, or below, a reference datum (zero on the gage). This reference datum is surveyed so that it can be related to elevation (msl).

By measuring the discharge at many stages, the USGS develops rating curves (or rating tables) that relate stage to discharge. Figure 12 shows an example of a rating curve. The force generated by moving water continually reworks the shape of the river channel. As a result, the relationship between river stage and discharge changes. Consequently, rating curves must be updated. When converting stage to discharge, or visa versa, it is important to use the rating curve from the period when the data was collected. When viewing historic records, it is also important to read the remarks to make sure that the gage has not moved and the reference datum has not changed.

During flooding, large rivers such as the Missouri and Mississippi rivers may have looped rating curves. The relationship between stage and discharge are different on the rising limb and falling limb of the hydrograph. Figure 13 shows a looped rating curve. In another section, it is explained that a uniform channel

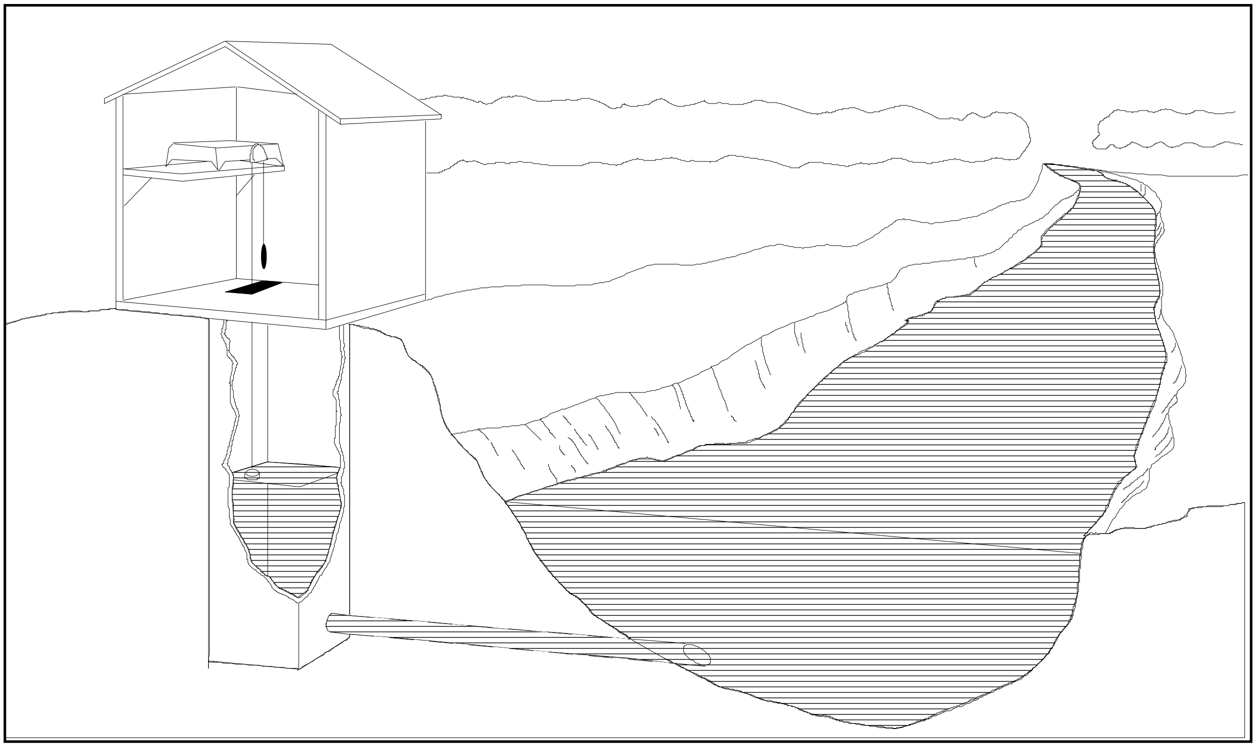


Figure 11. Example of a stream gaging station.

flowing at steady state reaches an equilibrium of velocity and stage. During flooding, flow does not remain constant. When the water is rising, the water surface slopes the same direction as the river bed. This increase in gradient accelerates the water and increases flow for a given stage. When the water is receding, the slope of the water surface is reduced or opposite the slope of the bed, resulting in decreasing flow (Figure 14). Under multiple flood peaks the rating curve may exhibit multiple loops (Bedient, 1988).

For many locations, the National Weather Service has determined the stage that water starts flowing out of its banks. This is called flood stage. The National Weater Service uses these numbers in conjunction with the river flood forecasts they make for the state. Table 2 lists flood stages and river forecast points for

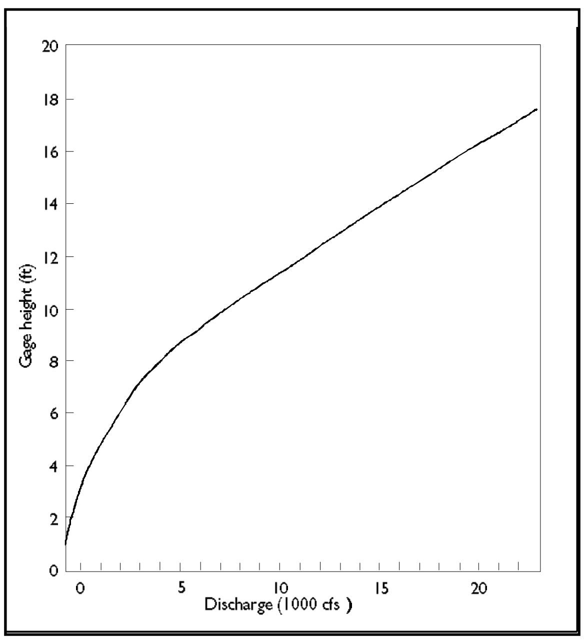


Figure 12. Rating curve.

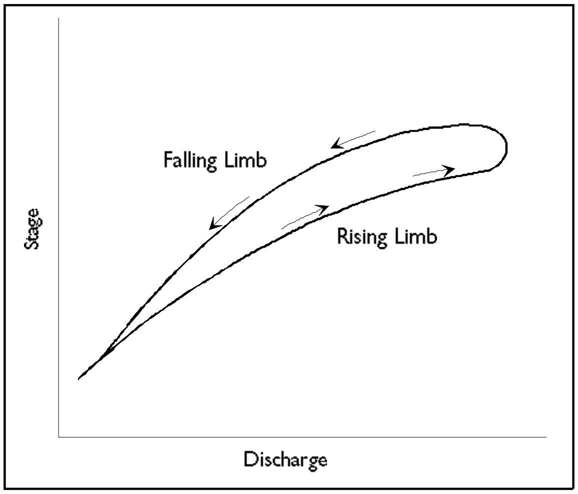


Figure 13. Loop rating curve.

locations in Missouri, and Figure 15 displays the location of those points.

RECORD DISCHARGE AND STAGE

Table 2 lists the highest stage and instantaneous discharge recorded at gaging stations in Missouri, and the date that those occurred. It should be noted that the date for the highest stage and largest discharge are not always the same. This is because the relationship between stage and discharge are not static.

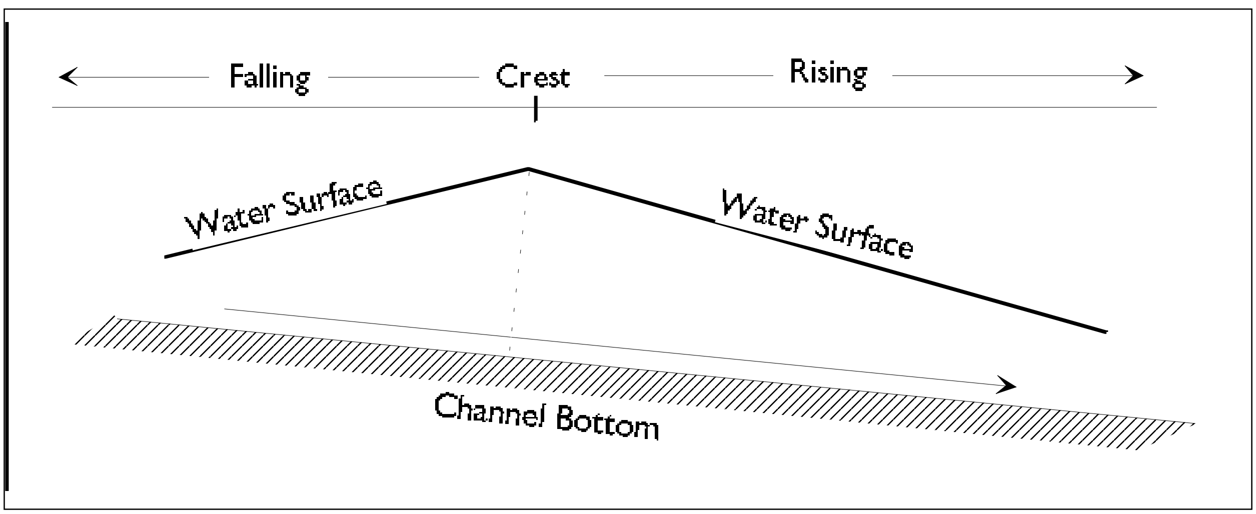


Figure 14. Illustration of a flood wave.

Table 1. National Weather Service river forecast points

Index	Location	Flood Stage
1	102 River at Maryville	14
2	Big Creek at Blairstown	20
3	Big Piney River at Fort Leonard Wood	13
4	Big River at Byrnesville	16
5	Black River at Annapolis	8
6	Black River at Clearwater Dam	N/A
7	Black River at Poplar Bluff	16
8	Blackwater River at Blue Lick	24
9	Blackwater River near Valley City	22
10	Blue River near Kansas City (Bannister Road)	24
11	Bourbeuse River at Union	15
12	Brush Creek at Kansas City	N/A
13	Chariton River near Novinger	20
14	Chariton River near Prairie Hill	15
15	Crooked River near Richmond	20
16	Cuivre River at Old Monroe	24
17	Cuivre River at Troy	21
18	Current River at Doniphan	13
19	Current River at Van Buren	20
20	Elk River at Tiff City	15
21	Fishing River near Mosby	18
22	Fox River at Wayland	15
23	Gasconade River at Hazlegreen	21
24	Gasconade River at Jerome	15
25	Gasconade River at Rich Fountain	20
26	Grand River near Brunswick	19
27	Grand River near Chillicothe	24
28	Grand River near Gallatin	26
29	Grand River near Pattonsburg	25
30	Grand River near Sumner	26
31	Jack’s Fork River at Eminence	10
32	James River at Galena	15
33	Lamine River near Otterville	15
34	Little Blue River at Kansas City (Knobtown)	27
35	Little Blue River near Lake City	18
36	Little Osage River at Horton	41
37	Little Platte River at Smithville	24
38	Maries River at Westphalia	10
39	Marmaton River at Nevada	44
40	Meramec River at Arnold	24
41	Meramec River at Eureka	18
42	Meramec River at Pacific	15
43	Meramec River at Steelville	12
44	Meramec River at Sullivan	15
45	Meramec River at Valley Park	16

Index	Location	Flood Stage
46	Middle Fabius River at Monticello	13
47	Mississippi River at Hannibal	16
48	Mississippi River at Louisiana	15
49	Mississippi River at Quincy	17
50	Mississippi River at New Madrid	34
51	Mississippi River at Grafton	18
52	Mississippi River at Canton	15
53	Mississippi River at Cape Girardeau	32
54	Mississippi River at Caruthersville	32
55	Mississippi River at Chester	27
56	Mississippi River at Gregory Landing	15
57	Mississippi River at L&D 24 Clarksville	25
58	Mississippi River at L&D 25 Winfield	26
59	Mississippi River at L&D 26 Mel Price	21
60	Mississippi River at St. Louis	30
61	Mississippi River at Thebes	33
62	Missouri River at Boonville	21
63	Missouri River at Gasconade	22
64	Missouri River at Glasgow	25
65	Missouri River at Hermann	21
66	Missouri River at Jefferson City	23
67	Missouri River at Kansas City	32
68	Missouri River at Miami	18
69	Missouri River at Napoleon	17
70	Missouri River at Sibley	22
71	Missouri River at St. Charles	25
72	Missouri River at St. Joseph	17
73	Missouri River at Washington	20
74	Missouri River at Waverly	20
75	Moniteau Creek near Fayette	16
76	Moreau River at Jefferson City	17
77	Nodaway River near Burlington Junction	18
78	North Fabius River at Monticello	17
79	North Fork White River at Tecumseh	20
80	North River at Palmyra	16
81	Osage River at Shell City	25
82	Osage River at St. Thomas	23
83	Petite Saline Creek near Boonville	16
84	Platte River at Sharps Station	26
85	Platte River near Agency	20
86	Platte River near Platte City	20
87	Sac River at Caplinger Mills	16
88	Salt River at New London	19
89	Shoal Greek at Joplin	14
90	South Fabius River at Taylor	9.5
91	South Grand River near Urich	24

Index	Location	Flood Stage
92	Spring River at Carthage	12
93	Spring River at Waco	19
94	St. Francis River at Fisk	20
95	St. Francis River at Patterson	16
96	St. Francis River at Wappapello Dam	N/A
97	Tarkio River at Fairfax	17
98	Thompson River at Trenton	20
99	Wakenda Creek at Carrollton	20

Note: Flood stages change periodically and should be verified by National Weather Service offices

Source: The following Individuals at National Weather Service Offices provided the information
Burns, Jack —NWSO St. Louis Hydrologic Service Area
Johnson, Gary — NWSO Springfield Hydrologic Service Area
Lamm, Mary—NWSO Paducah, Kentucky Hydrologic Service Area
Merchlewitz, Buzz —NWS Ohio River Forecast Center
Schwein, Noreen — NWS Central Region Headquarters
Veeneman, Joel —NWSO Pleasant Hill Hydrologic Service Area
Vochatzer, Jack— Missouri Basin River Forecast Center

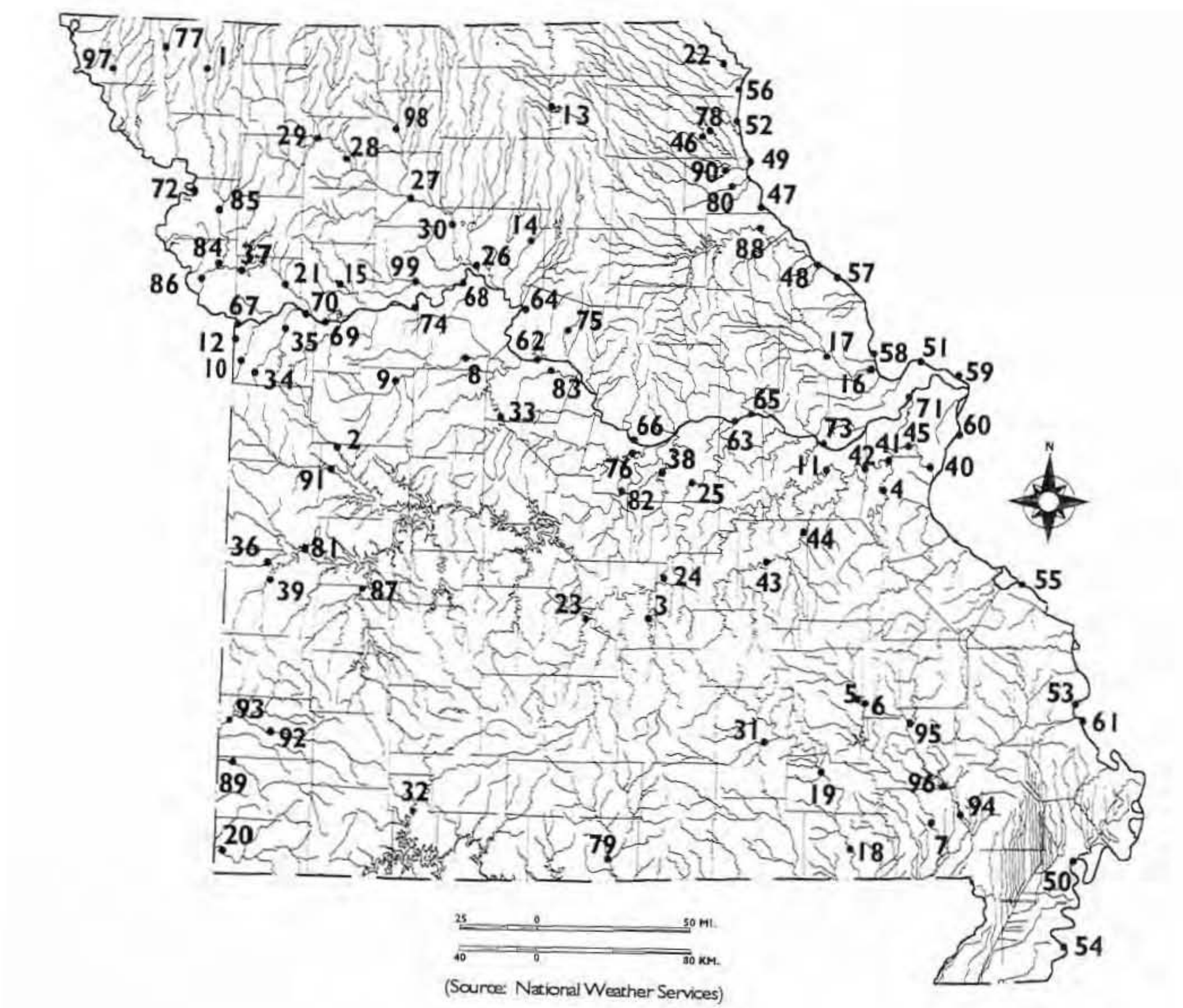


Figure 15. Locations of National Weather Service river forecast points in Missouri.

Table 2. Highest instantaneous discharge and stage at USGS gaging stations.

STATION ID	STATION NAME	RECORD	DISCHARGE (cfs)	DATE	STAGE (ft)	DATE
5495000	FOX RIVER AT WAYLAND	1922-94	26400	04/22/73	1.71	04/22/73
5496000	WYACONDA RIVER ABOVE CANTON	1922-94	17700	06/30/33	31.33	09/22/86
5497000	NORTH FABIUS RIVER AT MONTICELLO	1922-94	20700	04/22/73	33.03	04/22/73
5498000	MIDDLE FABIUS RIVER NEAR MONTICELLO	1946-94	17700	04/23/73	27.14	04/23/73
5500000	SOUTH FABIUS RIVER NEAR TAYLOR	1929-94	19700	06/08/47	19.50	06/08/47
5501000	NORTH RIVER AT PALMYRA	1935-94	57500	04/21/73	29.70	04/21/73
5502000	BEAR CREEK AT HANNIBAL	1937-94	3120	05/14/70	9.24	05/14/70
5502300	SALT RIVER AT HAGERS GROVE	1975-94	22000	04/03/83	18.80	04/03/83
5502500	SALT RIVER NEAR SHELBINA	1909-94	23000	06/07/47	27.40	06/07/47
5503800	CROOKED CREEK NEAR PARIS	1980-94	8100	07/01/93	12.68	07/01/93
5504800	SOUTH FORK SALT RIVER ABOVE SANTA FE.	1987-94	31800	09/23/93	28.66	09/23/93
5506500	MIDDLE FORK SALT RIVER AT PARIS	1940-94	45000	04/21/73	33.5*	04/21/73
5506800	ELK FORK SALT RIVER NEAR MADISON	1967-94	42300	04/21/73	33.40	04/21/73
5507600	LICK CREEK AT PERRY	1980-94	10900	09/23/93	21.96	09/23/93
5507800	SALT RIVER NEAR CENTER	1980-94	72800	07/29/81	32.62	07/29/81
5508000	SALT RIVER NEAR NEW LONDON	1858-94	74200	07/29/81	31.09	07/29/81
5508805	SPENCER CR BELOW PLUM CR NR FRANKFORD	1979-94	20300	09/22/93	18.54	09/22/93
5514500	CUIVRE RIVER NEAR TROY	1922-94	120000	10/05/41	33.40	10/05/41
5587450	MISSISSIPPI RIVER AT GRAFTON, IL	1880-29	598000	08/01/93	441.96	08/01/93
6813500	MISSOURI RIVER AT RULO, NE	1949-94	307000	07/24/93	25.37	07/24/93
6817700	NODAWAY RIVER NEAR GRAHM	1983-94	78300	07/23/93	26.16	07/23/93
6818000	MISSOURI RIVER AT ST. JOSEPH	1844-94	335000	07/26/93	32.07	07/26/93
6820500	PLATTE RIVER NEAR AGENCY	1924-94	60800	07/25/93	36.07	07/25/93
6821150	LITTLE PLATTE RIVER AT SMITHVILLE	1965-94	21000	08/13/82	36.44	08/13/82
6821190	PLATTE RIVER AT SHARPS STATION	1979-94	37800	07/26/93	36.43	07/26/93
6892350	KANSAS RIVER AT DESOTO, KS	1917-94	510000	07/13/51	37.30	07/13/51
6893000	MISSOURI RIVER AT KANSAS CITY	1844-94	541000	07/27/93	48.87	07/27/93
6893500	BLUE RIVER NEAR KANSAS CITY	1939-94	41000	09/13/61	44.46	09/13/61
6893793	L. BLUE R. BL LONGVIEW D.S. AT K.C.	1967-94	2870	05/15/90	12.96	07/06/93
6893890	EAST FORK LITTLE BLUE RIVER NR BLUE SPRINGS	1970-94	755	05/15/90	13.67	05/15/90
6894000	LITTLE BLUE RIVER NEAR LAKE CITY	1948-94	2300	08/13/82	27.94	09/14/61
6895500	MISSOURI RIVER AT WAVERLY	1929-94	633000	07/27/93	31.15	07/27/93
6897500	GRAND RIVER NEAR GALLATIN	1909-94	89800	07/07/93	41.50	07/07/93
6899500	THOMPSON RIVER AT TRENTON	1909-94	95000	06/06/47	25.70	06/06/47
6902000	GRAND RIVER NEAR SUMNER	1909-94	180000	06/08/47	42.52	07/10/93
6904050	CHARITON RIVER AT LIVONIA	1976-94	9200	07/18/82	28.33	07/18/82
6904500	CHARITON RIVER AT NOVINGER	1917-94	21500	07/24/93	25.71	07/24/93
6905500	CHARITON RIVER NEAR PRAIRIE HILL	1929-94	31900	04/23/73	21.96	04/23/73
6906200	EAST FORK LITTLE CHARITON R NR MACON	1972-94	1390	07/28/81	14.48	07/28/81
6906300	EAST FORK LITTLE CHARITON R NR HUNTSVILLE	1963-94	10400	06/27/81	19.30	09/02/82
6906800	LAMINE RIVER NEAR OTTERVILLE	1988-94	64800	04/11/94	27.98	04/11/94
6908000	BLACKWATER RIVER AT BLUE LICK	1905-94	54000	11/18/28	41.53	10/03/86
6909000	MISSOURI RIVER AT BOONVILLE	1844-94	755000	07/29/93	37.10	07/29/93
6918440	SAC RIVER NEAR DADEVILLE	1966-94	36100	09/25/93	27.56	09/25/93
6918460	TURNBACK CREEK ABOVE GREENFIELD	1966-94	42700	09/25/93	26.34	09/25/93
6918740	LITTLE SAC RIVER NEAR Mo.RRISVILLE	1969-94	29100	09/25/93	23.33	09/25/93
6919020	SAC RIVER AT HIGHWAY J BELOW STOCKTON	1974-94	14800	10/01/86	24.91	02/23/85
6919500	CEDAR CREEK NEAR PLEASANT VIEW	1909-94	37000	07/17/58	27.36	04/12/94
6919900	SAC RIVER NEAR CAPLINGER MILLS	1975-94	61500	04/12/94	30.95	04/12/94
6921070	POMME DE TERRE RIVER NEAR POLK	1969-94	34300	09/24/93	27.10	09/24/93
6921200	LINDLEY CREEK NEAR POLK	1957-94	31900	10/01/86	23.60	05/05/61
6921350	POMME DE TERRE RIVER NEAR HERMITAGE	1961-94	5910	05/05/70	12.15	05/05/70
6923150	DOUSINBURY CR ON JJ NEAR WALL STREET	1993-94	6780	09/25/93	10.14	09/25/93
6923250	NIANGUA RIVER AT WINDYVILLE	1993-94	44700	09/24/93	24.36	09/24/93
6923500	BENNETT SPRING AT BENNETT SPRINGS	1981-94	14400	10/01/86	11.10	10/01/86
6926000	OSAGE RIVER NEAR BAGNELL	1844-94	220000	05/19/43	48.80	05/19/43
6926500	OSAGE RIVER NEAR ST. THOMAS	1932-94	216000	05/20/43	43.80	05/20/43
6929315	PADDY CREEK ABOVE SLABTOWN SPRING	1993-94	8610	11/14/93	9.90	11/14/93
6930000	BIG PINEY RIVER NR BIG PINEY	1922-94	32700	12/27/42	20.70	12/27/42
6932000	LITTLE PINEY CREEK AT NEWBURG	1915-94	32500	08/14/46	16.60	06/17/85

STATION ID	STATION NAME	RECORD	DISCHARGE (cfs)	DATE	STAGE (ft)	DATE
6933500	GASCONADE RIVER AT JEROME	1897-94	136000	12/05/82	31.34	12/05/82
6934000	GASCONADE RIVER NEAR RICH FOUNTAIN	1922-94	134000	12/06/82	33.27	12/06/82
6934500	MISSOURI RIVER AT HERMANN	1844-94	750000	07/31/93	36.97	07/31/93
7010000	MISSISSIPPI RIVER AT ST LOUIS	1844-94	1080000	08/01/93	49.58	08/01/93
7013000	MERAMEC RIVER NEAR STEELVILLE	1915-94	51200	06/18/85	26.15	06/18/85
7014500	MERAMEC RIVER NEAR SULLIVAN	1915-94	77300	06/09/45	32.00	06/09/45
7015720	BOURBEUSE RIVER NR HIGH GATE	1965-94	49300	12/03/82	23.65	12/03/82
7016500	BOURBEUSE RIVER AT UNION	1897-94	73300	12/05/82	33.80	12/05/82
7017200	BIG RIVER AT IRONDALE	1965-94	49100	11/14/93	28.95	11/14/93
7018100	BIG RIVER NEAR RICHWOODS	1984-94	59800	09/23/93	30.33	09/23/93
7018500	BIG RIVER AT BYRNESVILLE	1915-94	63600	09/25/93	29.37	09/25/93
7019000	MERAMEC RIVER NEAR EUREKA	1904-94	145000	12/06/82	42.89	12/06/82
7020500	MISSISSIPPI RIVER AT CHESTER, IL	1927-94	1000000	08/07/93	49.74	08/07/93
7034000	ST. FRANCIS RIVER NEAR ROSELLE	1987-94	45700	11/14/93	26.50	11/14/93
7035000	LITTLE ST. FRANCIS RIVER AT FREDERICKTOWN	1984-94	25100	11/14/93	26.50	11/14/93
7035800	ST. FRANCIS RIVER NEAR MILL CREEK	1987-94	130000	11/14/93	33.10	11/14/93
7036100	ST. FRANCIS RIVER NEAR SACO	1984-94	161000	11/14/93	36.10	11/14/93
7037000	BIG CREEK AT DES ARC	1987-94	25700	11/14/93	16.85	11/14/93
7037500	ST. FRANCIS RIVER NEAR PATTERSON	1915-94	155000	12/03/82	35.77	12/03/82
7039500	ST. FRANCIS RIVER AT WAPPAPELLO	1941-94	22300	04/16/45	31.34	5/29-31/91
7050700	JAMES RIVER NEAR SPRINGFIELD	1956-94	41100	09/25/93	19.45	09/25/93
7052500	JAMES RIVER AT GALENA	1922-94	73200	09/25/93	33.46	09/25/93
7057500	NORTH FORK RIVER NEAR TECUMSEH	1945-94	133000	11/19/85	28.10	11/19/85
7061500	BLACK RIVER NEAR NEAR ANNAPOLIS	1939-94	109000	11/14/93	27.38	11/14/93
7062500	BLACK RIVER AT LEEPER	1904-94	40900	12/03/82	15.15	12/03/82
7063000	BLACK RIVER AT POPLAR BLUFF	1904-94	65600	12/04/82	21.68	12/04/82
7065495	JACKS FORK AT ALLEY SPRING	1993-94	48700	11/14/93	21.97	11/14/93
7066000	JACKS FORK AT EMINENCE	1895-94	58500	11/15/93	17.82	11/15/93
7067000	CURRENT RIVER AT VAN BUREN	1904-94	125000	08/21/15	27.39	11/15/93
7068000	CURRENT RIVER AT DONIPHAN	1904-94	122000	12/03/82	25.49	12/03/82
7071000	GREER SPRING AT GREER	1981-94	1770	12/03/82	2.97	12/03/82
7071500	ELEVEN POINT RIVER NEAR BARDLEY	1915-94	49800	12/03/82	21.64	12/03/82
7186000	SPRING RIVER NEAR WACO	1923-94	*151000	09/26/93	34.06	09/26/93
7186475	CERTER CREEK BELOW CARL JUNCTION	1993-94	36200	09/25/93	17.84	09/25/93
7187000	SHOAL CREEK ABOVE JOPLIN	1924-94	*62100	05/18/43	*16.8	05/18/43
7189000	ELK RIVER NEAR TIFF CITY	1940-94	**13700	04/19/41	***28.4	04/19/41

* Former site and datum
** From rating curve extended above 60,000 cfs on basis of slope-area measurement of peak flow.
*** From flood mark.

FLOOD STATISTICS

Exceedance probabilities are a type of frequency analysis that uses historic data to provide an estimate of the likelihood that a flood of a given magnitude will occur. There is a probability (p) that a given discharge will be equaled or exceeded in any given year. Using frequency analysis we derive a discharge with a certain exceedance probability: e.g., 1% (0.01), 5% (0.05), 10% (0.10). Exceedance probabilities are commonly discussed in reference to their recurrence intervals. The recurrence interval for a certain exceedance probability is 1/p. An exceedance probability of 0.01 would have a 100-year recurrence interval. Table 3 gives recurrence intervals for common exceedance probabilities.

Table 3. The relationship between exceedance probability and recurrence interval.

Exceedance Probability	Recurrence Interval
0.50 (50%)	2-year
0.10 (10%)	10-year
0.05 (5%)	20-year
0.02 (2%)	50-year
0.01 (1%)	100-year
0.002 (0.2%)	500-year

Recurrence interval should not be confused with the duration or time between occurrences. Statistically, each year has the same probability that a 100-year flood will occur (1 percent chance of that discharge being equaled or exceeded); and it is possible to have several 100-year floods in a short period of time.

As the recurrence interval increases well beyond the years of record used to generate the statistics, the results are less certain. Many researchers question the validity of 500-year statistics because of this uncertainty. If for nothing else, these statistics are useful as general indicators of the relative magnitude of very rare events.

Exceedance probability analysis assumes that past records predict what may occur in the future, and floods are random and their occurrences follow a normal distribution. Many believe that climate is cyclic. The cyclic pattern can be seen in the historic Palmer Indices that are found in the second part of this publication. If the data used to generate the statistics are from a wet or dry period, the results would only be representative of that time period. There are other complicating factors that should be considered when using exceedance probabilities. For example, global warming and land use changes that alter rainfall or runoff would affect the distribution, frequency and magnitude of floods. It can be difficult adjusting historic records to account for these changes.

Historic gage data is one basis for calculating flood recurrence intervals. Figure 16 shows the length of daily streamflow records for stream gages that are located in Missouri. About one third of the gaging stations have record lengths shorter than 10 years. Only 62 gages (22 %), have records in excess of 50 years.

There are many rivers around the state that do not have gages. For those rivers, methods have been developed to estimate peak flow and flood volumes (or duration). Appendix 1 has a discussion of commonly used models and regionalized equations that are applicable to Missouri.

RIVER HYDRAULICS

The relationship between water surface elevation, stream discharge and velocity are important aspects in understanding floods.

Water is pulled down hill by gravity. It is held back by resistance from the stream channel. In a uniform channel these two forces strike a balance to achieve constant depth and velocity. The relationship is represented in Manning's equation:

$$V = CR^{.66}S^{.5}/n$$

where:

- V = velocity
- C = 1.0 SI units or 1.49 US units
- R = hydraulic radius, the ratio of the cross sectional area to the wetted perimeter (A/wp)
- S = energy gradient (approximately the slope of the water surface)
- n = manning roughness coefficient (gets larger as roughness increases)

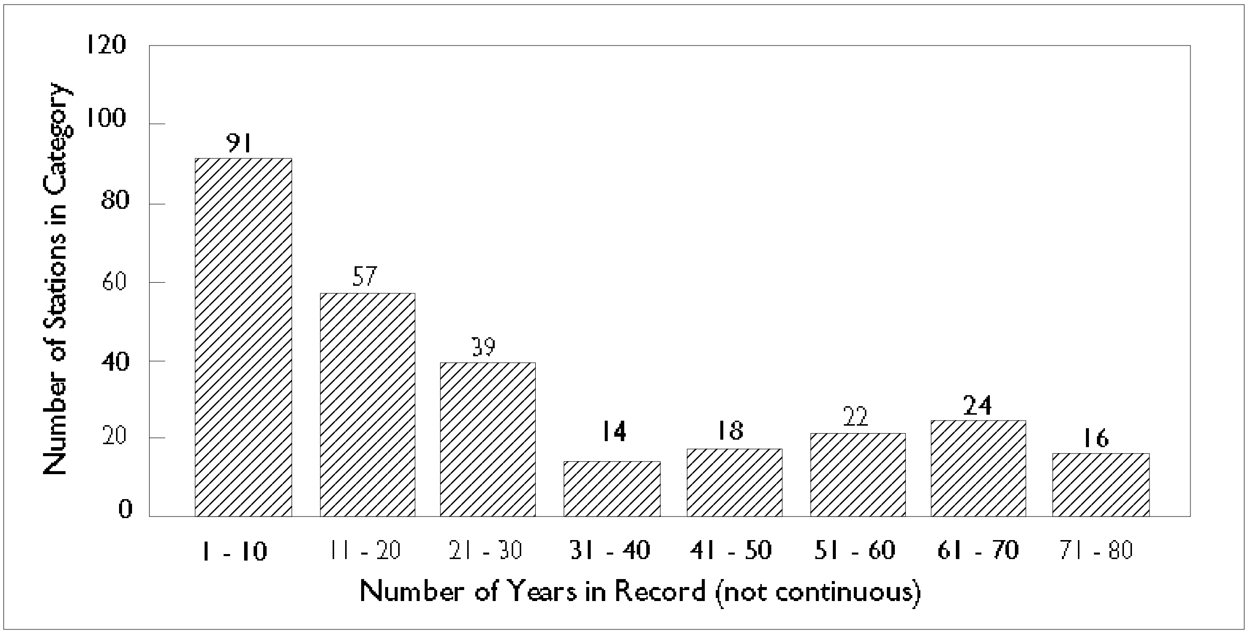


Figure 16. Length of record for active and historical gaging stations in Missouri.

From this equation it can be determined that velocity increases with increased channel slope, and decreases as roughness (friction) increases.

Stream discharge can be determined using the equation:

$$q = VA \quad \text{or} \quad (CR^{.66}S^{.5}/n)A$$

where:

q = discharge (flow rate)

A = cross sectional area (width x average depth)

If water in a stream channel has a cross sectional area of one square foot and is traveling down stream at a velocity of one foot per second, the stream has a discharge of one cubic foot per second (1 cfs).

From these equations we can see that water elevation (stage) for a given discharge can be affected by changing stream width, or by altering the roughness of the channel (frictional losses): For a given discharge, if the width is decreased the depth increases to maintain the cross sectional area; and as roughness increases, velocity decreases and the cross sectional area increases to compensate for the drop in velocity.

When considering modifications to a stream channel or flood plain, it is important to consider the effect the alterations would have on both depth and velocity. For example, you could encroach on the flood plain by building a bridge or a levee without raising flood height by also reducing the roughness (frictional losses). The trade-off is that you would also be increasing velocity. Not only is water depth a factor in flood damages, so is velocity.

There are hydraulic models which estimate flood heights for a given discharge. Appendix 1 discusses some of the common models.

TYPES OF FLOODS

Floods are often discussed as if all flooding were the same. However, flooding and flood problems differ greatly across the state. This section describes some of the unique characteristics of flooding in Missouri.

Flash Floods

Flash flooding happens when there is very fast response to rainfall, a sudden dramatic peak with a very short lag time. Flash flooding can jeopardize safety and cause property damage. According to an investigation by the Missouri Department of Health, there were

49 flood-related deaths during the summer flood of 1993. Thirty-five of those deaths, or 71 percent, were attributed directly to flash floods.

Low-water crossings are a dangerous setting when flash flooding occurs. It is easy to underestimate the depth, velocity, or rate that the water is rising. Vehicles can be swept away when they enter flooded areas. There were 26 motor vehicle deaths among the 49 deaths recorded in the 1993 summer/fall floods. Twenty were caused by flash floods. During the April 1994 flooding, seven deaths were recorded. Five deaths involved motor vehicles in flash flood situations (SEMA, 1994).

Some of the factors that relate to flash flooding are intense rainfall, land use, and topography. Intense storms that drop large amounts of rainfall in a short period of time are, possibly, one of the biggest factors causing flash flooding. Missouri can be prone to these types of storms. Holt, Missouri, holds a world record with 12 inches of rainfall within a 42 minute time period. This event occurred on June 22, 1947 (Lindsey, etc., 1975). Land use is also a significant factor contributing to flash floods. As discussed in the section on hydrographs, impervious areas associated with urbanization increases the amount of runoff and decreases lag time, thereby increasing the flash flood potential. Topography is also a factor. Areas with steep terrain are most prone to flash floods.

Floods on Streams and Rivers

Stream or river flooding occurs along the flood plains of our streams and rivers. Their onset is less violent than what might typify flash floods. This type of flooding can be significant, as far as damages caused, because of the wide area that can be affected. Many of the river systems that are prone to this type of flooding have some sort of structural flood-control measures. This usually takes the form of flood-control impoundments and levees.

Flood-control impoundments come in many sizes. They range in size from the large systems operated by the U.S. Army Corps of Engineers, to small impoundments that are installed in the upper ends of the watershed (i.e. PL 566 projects). Table 4 lists Corps reservoirs located in Missouri and the flood storage capacity of each reservoir.

Levees also come in many shapes and sizes. They range from small agricultural levees, which offer protection from low level flooding (almost all offering less than 25-year flood protection and commonly offering less than 5- to 10-year flood protection), to very large levees that protect urban areas (commonly offering greater than 100-year flood protection).

Excessive rainfall over broad areas are a major contributor to floods on streams and rivers. Some of our rivers have very large drainage areas (the Missouri River Basin is about 529,000 square miles at the mouth, and the Mississippi River at New Madrid has a watershed of over 900,000 square miles).

Floods on rivers with large drainage areas can last for an extended period. For example, the Missouri River at Boonville was above flood stage for almost two months during the 1993 flood. Floods that last a long time, require special considerations. These include displacement of people from their homes or businesses, access and travel route problems. Levees should be designed to withstand long periods of saturation and piping from high hydrostatic pressure. Internal drainage behind flood control structures (levees) can be a problem. Most agricultural levees use gravity to drain water that accumulates from local rain and runoff. If the drain outlet is submerged water ponds behind the levee. This can prevent planting or harvesting, stunt growth or kill the crops all together.

Flooding is more likely to occur when soil moisture levels are high before heavy rainfall and flooding occurs. When soils are already saturated runoff volume increases and occurs much quicker. Runoff in saturated areas is much like that of impervious areas.

Ponding

There are many areas in the state that experience flooding from ponding water. This happens around lakes, ponds and sinkholes.

Table 4. Flood control storage in Corps Reservoirs (approximate storage capacity in acre-feet)

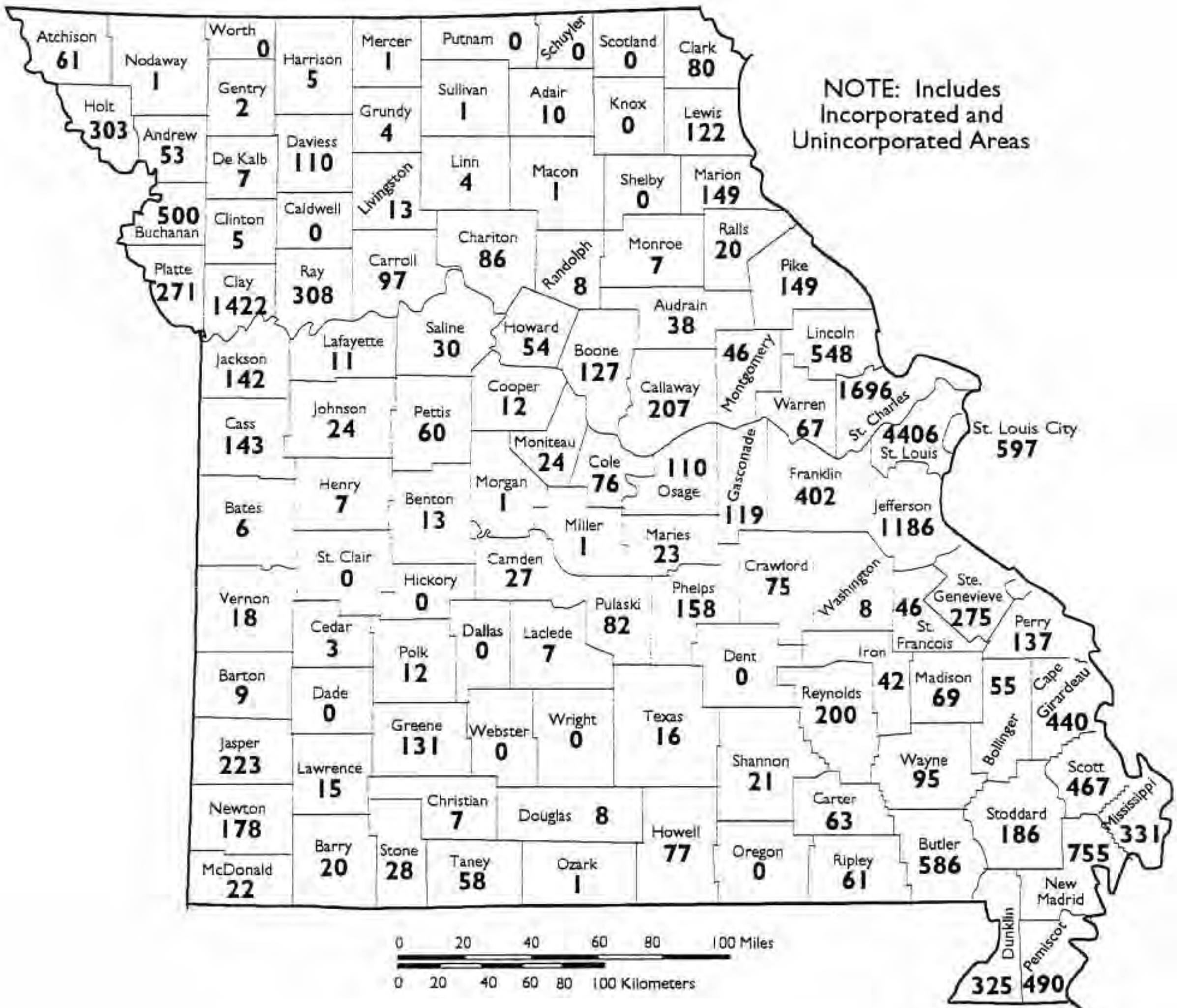
Reservoir	Total Capacity	Flood Control
Wappapello[1]	613,000	582,000
Clearwater[1]	413,000	391,000
Norfork[1]	1,983,000	732,000
Bull Shoals[1]	5,408,000	2,360,000
Table Rock[1]	3,462,000	760,000
Stockton[1]	1,674,000	774,000
Pomme de Terre[2]	644,000	407,000
Harry S Truman[2]	5,209,000	4,006,000
Longview[1]	46,900	24,300
Blue Springs[1]	26,950	14,800
Smithville[1]	246,000	9,200
Long Branch[1]	65,000	29,000
Mark Twain[1]	1,428,000	884,000

[1]Source: Corps, 1995, Water Resources Development by the U.S. Army Corps of Engineers in Missouri.
[2]Source: Corps, undated, Summary of Engineering Data—Lower Missouri River Basin Projects.

It also occurs where the topography is flat. The Bootheel area is prone to widespread flooding because its relatively flat topography. During heavy rainfall, water accumulates because of slow runoff rates, and creates shallow flooding. This type of flooding can cause damages, especially to crops, but, because it is water that is ponding, there is little velocity to create the hazard that occurs along rivers.

FLOOD DAMAGES IN MISSOURI

The National Flood Insurance Program is the primary federal program related to flooding which helps to pay for flood damages and guides proper development of flood-prone areas. Not all eligible communities with high potential for flood damages participate in the National Flood Insurance Program. In fact, only 523 communities were participating in

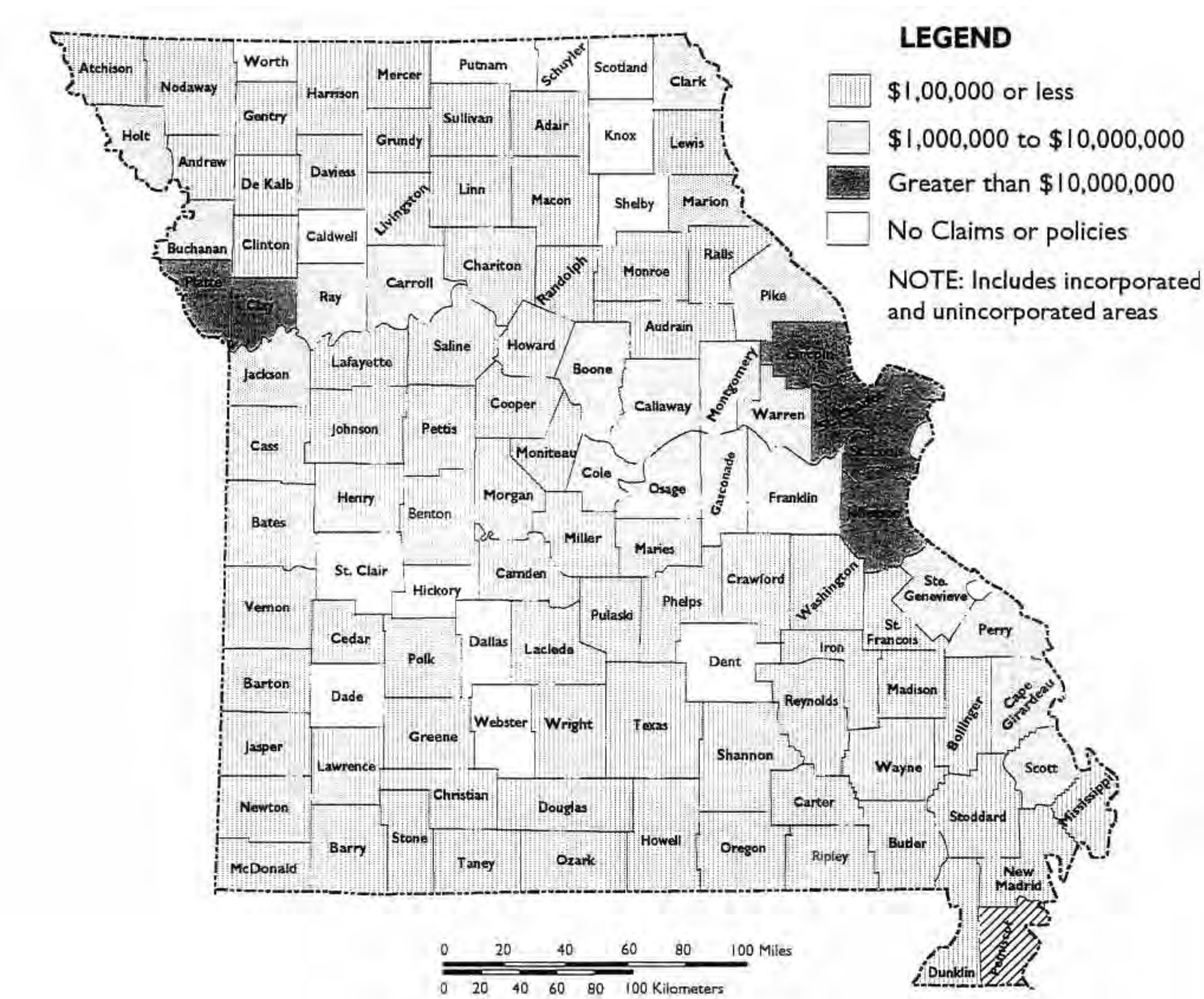


Source: Federal Emergency Management Agency

Figure 17. National Flood Insurance Program, number of policies (data current as of July 31, 1995)

the NFIP as of May 1, 1996 (community is defined in the NFIP as local jurisdiction, i.e., city, town or county). As of this same date, there were 101 communities that had Special Flood Hazards identified that were not participating in the National Flood Insurance Program.

Insurance enrollment is voluntary and not every business or homeowner that is prone to flood damages chooses to carry flood insurance. Still, the number of NFIP polices and flood claims paid provides useful insight into the locations of flood problems. Assuming that people who perceive that they are flood-prone carry flood insurance, and that claims paid represent flood damages, the number of policies and dollar amount paid provide a survey of areas with flooding problems (residential and business). As might be suspected the greatest number of flood policies and dollars paid are around the urban centers of St. Louis, St. Charles, and Kansas City. As can be seen in Figure 17, St. Louis County has about 4,400 policies, City of St. Louis has about 600

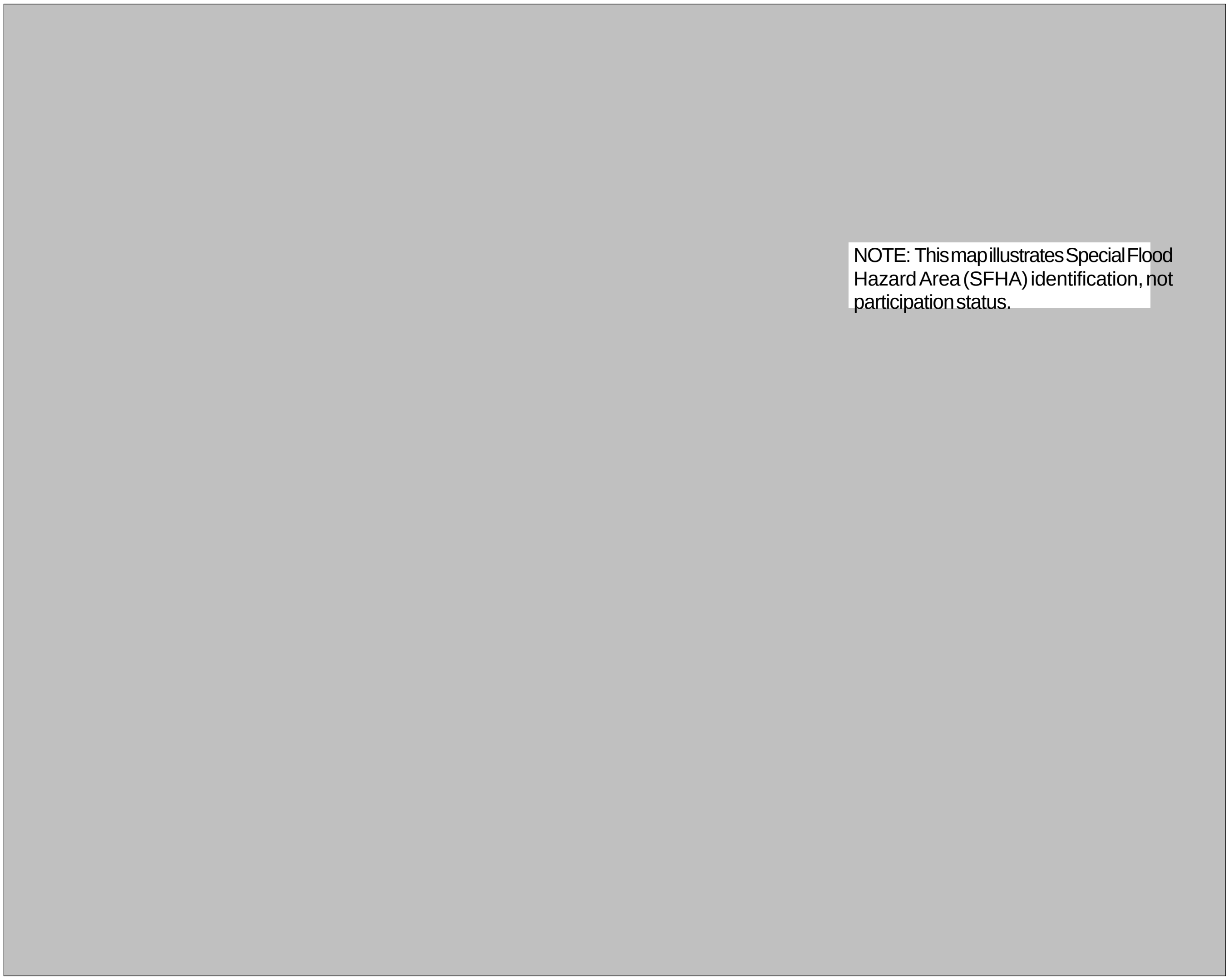


Source: Federal Emergency Management Agency

Figure 18. National Flood Insurance Program claims paid since 1978 (data current as of July 31, 1995)

policies, St. Charles County has about 1,700 policies and Clay County has about 1,400 policies in effect (numbers include incorporated and unincorporated areas, as of July 31, 1995). These same areas have had claims paid of around $98 million, $5.6 million, $97 million, and $26 million respectively (dollars paid include incorporated and unincorporated, from 1978 through July, 31, 1995). Figure 18 shows the claims paid from 1978 to 1995 for the state.

Figure 19 shows the communities (incorporated and unincorporated areas) that have Special Flood Hazard Areas identified by the



Source: Federal Emergency Management Agency

Figure 19. Communities with Special Flood Hazard Areas identified by National Flood Insurance Program (data current as of October, 1994).

National Flood Insurance Program (NFIP). As expected, the highest concentration is around urban centers where there is a greater density of separate communities. Beyond that, Special Flood Hazard Areas are spread across the state. It should be noted that not all areas of the State have Special Flood Hazard Areas identified. This includes counties that have major rivers running through them. As of May 1996, there were 74 communities participating in the NFIP, with no Special Flood Hazard Areas identified by the NFIP.

HISTORIC FLOODS

A brief overview has been compiled to provide a glimpse of historic floods in Missouri's past. The following excerpts are unedited quotes from the sources listed.

1826

(Source: Dyer, 1993)

Most of the residents left the town (Franklin) in the years following the notable Spring Rise of 1826, a description of which appears in the **Missouri Intelligence and Boon's Lick Advertiser** of May 12, 1826: The Missouri River has risen higher the present season than has been known for thirty years. We learn by a gentleman from Council Bluffs that all the bottom lands between that place and this were overflowed-whole farms inundated, and the crops destroyed, fences swept away, hogs and cattle drowned, and the inhabitants obliged to remove.

Although this particular flood did not deal the final death blow to the town, it did mark the beginning of the end of Franklin.

1844

(Source: Dyer, 1993)

The Flood of 1844 was, of course, the most notable flood of the 19th century on the Missouri River, and until the flood of 1993, was the all-time record flood on the Missouri.

The **Missouri Register**, June 18, 1844, gave a vivid description of the 1844 flood: UNPARALLELED MOUNTAIN RISE IN THE MISSOURI AND DISTRESSING CALAMITY!! Never since Missouri has been a settled country has such a flood water made its appearance in our river as is now bursting from its banks and flooding all the low lands in every direction. It has been quite high all the spring, but for the last five or six days it has risen an inch an hour upon an average. It is still rising at the same rate, spreading ruin and distress in many places from bluff to bluff.

Above, near Independence, we understand the rise was so rapid on Friday or Saturday night last, that many people were lost, and every thing they had swept away before they had time to help themselves. Such distress is unprecedented in Missouri, and where it will end, should the river continue to rise forty-eight hours longer, it is impossible to form an opinion.

The damage already sustained is incalculable. And what adds much to this distressing calamity, is the fact that there has been so much rain throughout the country the past spring that the crops are severely injured, generally; and it still continues to rain so much that farmers in the back country can scarcely get an opportunity, in many places, of tending their crops at all. A more distressing season than the present bids fair to be, has never manifested itself in Missouri. The floods must eventually check business greatly along our rivers, and ruin thousands of farmers bordering on them.

Another description of this 1844 flood was given by the government weather service: The stage reached on the present scale of river measurements was 37 feet on June 20 at Kansas City, 16 feet above the danger line. At Boonville the river reached 33.6 feet two and a half days later, which was 13.6 feet above the danger line at that place.

The flood was caused by the coincidence of unusually heavy and protracted rains, with what is known as the June rise, the melted snows from the headwaters. It is said that about the middle of April the rains began to fall in brief showers nearly every other day. After a few weeks it began to rain every day. It poured down for days and weeks without cessation.

The river was rising quite rapidly, but no danger was anticipated, for the oldest settler had never seen a general and destructive overflow and did not know that such a thing could occur. The river continued to rise, however, at the rate of twelve to eighteen inches a day until June 5, when it went over its banks, and situation became alarming. The channel was full of driftwood. Occasionally a log house floated down with chickens and turkeys on the roof. In several instances men, women and children were seen on the tops of houses floating hither and thither, and turned and twisted about by heavy logs and jams, but the people were rescued by parties in skiffs.

On June 20 the water had reached its highest point, and the next day began to fall, but the damage done seemed absolute and the ruin complete. The flood extended from bluff to bluff, generally two miles. There was not an acre of dry land in the river bottoms from Kansas City to the mouth of the river.

"Various towns up and down the river, including Boonville, recorded the level of the 1844 flood with stone markers. Boonville's marker is under the present highway bridge on the south side of the river and during the Flood of '93 many of us marveled as we watched it go under water for the first time since it was first set in place.

1881

(Source: Dyer, 1993)

This flood crested at 24.6 feet at Boonville, which is not a remarkably high crest in 20th century terms, but this was in the time before levees were constructed. The flood was vividly described in the **Boonville Weekly Advertiser**, May 6, 1881: THE MAD MISSOURI, The present rise in the Missouri River is the greatest since the noted flood of 1844. Miles in breadth of angry waters are rushing to the Gulf, covering islands, bottom fields, houses, dikes and railroad tracks in their mad course.

The principal damage in the earlier stages of the flood was suffered at Kansas City where part of the town was, and is yet, inundated. All railroad communication except by the Missouri Pacific is cut off, and ferry and other boats are engaged constantly in rescuing people from their submerged houses.

As the flood came on down it spread out over miles of the low bottom lands on the north side off the river, destroying crops, drowning stock of all kinds, and making people flee for life to the high lands. The farmers living in the Carroll County bottoms have given up all hope of making a crop.

The Government dike and the approach to the bridge of the C.& A. Railway at Glasgow is washed entirely away and trains have been abandoned there for several days.

The river here at home looks like an inland sea, stretching as it does to the limit of the view in the bottom on the Howard County side. The waters broke over above the point and are running around the farms immediately opposite here, leaving them on an island. Incalculable damage has been done to crops and farm property of all kinds. Even the dwelling houses that have been surrounded careen over on their sides when the waters subside.

1903

(Source: Dyer, 1993)

The flood of 1903 was particularly severe in the Boonslick area. Following a series of heavy rains during the last week in May, the river began rising rapidly. On June 5th the river crested at Boonville at 30.8 feet and the **Central Missouri Republican** newspaper reported that: Much damage has been wrought by the flood in the vicinity of Boonville. Houses on the islands and lowlands were washed away, crops destroyed and much livestock drowned. Most of the corn and wheat being grown in the bottoms was ruined and the Katy railroad lost much of its roadbed between the river and Franklin Junction as well as suffering considerable damage to its tracks all the way to the mouth of the Missouri River.

(Source: Burnes, 1993)

May 31, 1903-The entire West Bottoms area flooded as the result of rains over the previous weeks. The disaster was said to be a duplicate of an 1844 flood that didn't cause much damage in what was then a relatively undeveloped area.

This time, however, water swept away 16 of 17 bridges across the Missouri and Kaw (Kansas) rivers. About 20 persons died and more than 22,000 were left homeless by the high water.

The flood cut off the city's water supply. Fearing fire, city leaders prohibited the use of gasoline or kerosene for illumination. This resulted, The Kansas City Star reported, in the city being in virtual darkness.

1904

(Source: Cramer, 1972)

A cloudburst on the headwaters of the creeks and rivers on March 26, 1904, caused a disastrous flood that was general all over the County. It remains in the minds of old citizens who experienced it as “The Flood” like the flood in the Bible. At Williamsville, although Black River is a half a mile from the town, the floodwaters were eighteen inches deep in the Gladden Hotel. Similar flooding elsewhere badly damaged homes and businesses. Forty ranks of stovewood were carried away.

The same inundations occurred at Greenville and Chaonia, which was submerged.

1908

(Source: Cramer, 1972)

Another flood of the St. Francis River in January 1908 was bad enough to put the railway bridge out of commission.

1915

(Source: Cramer, 1972)

The worst flood in a century occurred Sunday, August 26, 1915. Chaonia was submerged and at Greenville water was five feet deep in the town. Many homes were seriously damaged and people lost their furniture and other belongings. When the water went down Greenville was a sickening sight covered with debris and dead animals. The wooden approach of the highway bridge above the town was out and the railway bridge of the Ozark valley railway was damaged.

1927

(Source: U.S. Army Corps of Engineers, 1994)

The flood of 1927 on the Mississippi River from Grafton, Illinois, southward was unusually high. The river crested at St. Louis on April 26 at 36.1 feet and remained above flood stage from April 13 to May 1. The maximum discharge at St. Louis was 889,000 cfs. Although this flow has probably been overestimated, the 1927 flood was the flood of record for the lower Mississippi River Valley.

(Source: U.S. Army Corps of Engineers, 1973)

All during the winter of 1926-27, heavy rains fell up and down the main stem (Mississippi River), and in the flood plains of the tributaries. The low-water period, which normally starts about the middle of October and continues into the winter, didn’t come to pass. By February, the ground was soaked, everywhere, unable to absorb any more rainfall, should it occur.

But rains did continue, and here and there, alongside the river floods began to crumble the private walls people had built to hold back the waters.

The ensuing damage was terrifying. Farms, towns and parts of cities were submerged beneath rampaging tides of water. All told, 25,000 square miles went under. Property damage amounted to about $236 million, which is equivalent to more than $1 billion today. At least 300 lives were lost, and 637,000 persons were displaced. A total of 25,000 horses and mules, 50,000 cattle and 150,000 swine drowned.

A man in Vicksburg, Mississippi, recalled: “When the old levee broke, you could hear the water roaring for miles.” The river crested there at 58 feet.

1935

(Source: Cramer, 1972)

Flood stage at Black Bridge on the St. Francis River is 16 feet. On March 11, 1935, the river reached 30.7 feet; “this flood broke many of the levees in Butler County farther south.”

1951

(Source: Burnes, 1993)

July 13, 1951-The Kaw River (Kansas River) flooded over levees in Armourdale, Argentine and the central industrial district. Observers estimated that the Kaw, fed by weeks of excessive rains in Kansas, approached a flow of 500,000 cubic feet a second during the flood, nearly twice the estimated volume during the 1903 flood.

The stain - 17 feet above the store’s ground floor - shows just how high the water rose in

July 1951 during the devastating Friday the 13th flood that killed 28 persons.

About 17,000 people were evacuated in the 1951 flood. An estimated 12,000 head of livestock, mostly hogs, were lost to the water.

The flood knocked out a pumping station that supplied more than half of Kansas City's water. As a result, all but essential business activity ceased for four days, and hundreds of residents had to haul water to their homes.

(Source: Dyer, 1993)

The flood of 1951 reached 32.8 feet at Boonville and topped or breached all the levees in the area.

1952

(Source: Filbert, 1992)

Elwood in fact, took the biggest bath. On April 14 evacuation there was nearly 60 percent complete and reports of looting began to spread, along with stories of "movers" charging exorbitant rates to help folks get their belongings to high ground.

Within a few days , Elwood was a ghost town, patrolled only by boating law enforcement officials and some of the 3,000 army and National Guard troops on hand to help handle the emergency.

By Sunday, April 20, 187,000 acres were inundated and damage estimates from Rulo, Nebraska to St. Louis were put at $13 million.

(Light & Power Co., 1991) The summer 1952 issue of Contact, a magazine published by the St. Joseph light & Power Co., dedicated the centerfold to coverage of the flood. It reported the facts thus: *The belligerent Missouri River, out on the greatest spree of its recorded history, rose more than 10 feet above flood stage last April 22 when the crest of 27.2 feet was reached.*

The major breakthrough, however, was made across a sharp 'U' bend north of St. Joseph, temporarily isolating Rosecrans field and some 1,500 acres of rich bottom farm land.

1965

(Source: U.S. Army Corps of Engineers, 1994)

The April 1965 flood was the flood of record for the 700-mile reach of the Mississippi River between Royalton, Minnesota, 100 miles upstream of Minneapolis, to just below Hannibal, Missouri. The 1965 flood exceeded prior records by several feet at numerous gaging stations in the basin and caused $225 million damage to public and private properties. Of this, $173 million damage occurred along the main stem of the Mississippi River.

1973

(Source: U.S. Army Corps of Engineers, 1994)
(note: upper Mississippi River and lower Missouri River)

Periods of snow and severe cold temperatures occurring during December 1972 and early January 1973 alternated with short periods of warmer weather accompanied by rainfall. Unseasonably warm weather during the second half of January and all of February caused considerable surface thawing and melting of the snow cover. Flooding was generally caused by torrential rains falling on saturated soil and rivers with extremely high base streamflow. The peak flow was 414,000 cfs on April 25. In 1973, the crest at Hannibal, Missouri, and Quincy, Illinois, was 4 feet higher than in 1965. The flood displaced 10,000 people and inundated 180,000 acres. The river was above flood stage at Hannibal for 106 days.

(Source: Wood, 1973)

The St. Louis area's worst flood in history forced thousands more from their homes Thursday as the Missouri River spread over 40 percent of St. Charles County and the rain-bloated Mississippi River swelled to record-breaking high.

St. Charles County authorities estimated that more than 5,000 persons have been dislocated by the flooding Missouri, now covering more than 3,000 square miles of the county with the topping of at least six levees after the Missouri-Kansas-Texas levee finally gave way to the floodwaters late Wednesday.

(Source: St. Louis (AP), 1993)

By April 30 of that year the federal government had declared 82 of Missouri's 114 counties as flood disaster areas. From the time the Mississippi first reached flood stage on March 17, it was out of its banks at St. Louis for 80 days, creating sodden misery for people who dared live too close to it.

Homes and farms were inundated for months and 11 deaths were blamed on the high water. Damages were estimated in the hundreds of millions of dollars.

At the peak of the flooding, caused by record rains in March, water from the Mississippi, Missouri and Illinois rivers and their tributaries covered more than 10 million acres of land in seven states.

1977

(Source: Calkins, 1978)

On Monday night, September 12, 1977, approximately 14 inches of rain fell in a concentrated area within Kansas City, Mo. The downpour fell on ground already saturated by a 4-inch rainfall the previous day.

The drainage runoff from the drenching rain exceeded anything recorded in Kansas City's history. It resulted in 25 deaths, about $6 million in property damage and untold misery to thousands of residents.

The flood water inundated about 300 vehicles. Most of the cars were swept down the bed of Brush Creek which suffered the heaviest concentration of water. We estimate that about 35,000 cfs flowed down the stream channel at the height of the storm. This compares with the stream's previous flood record of 4300 cfs.

Many deaths were the result of vehicle occupants being swept along with the flood. The surge of the waters prevented the drivers from steering their vehicles clear of the flood stream.

Flood waters had filled basements and portions of first floors of most commercial buildings in the exclusive County Club Plaza area bordering the creek. In addition, hundreds of homes along tributary streams suffered severe flooding. Overland flows in some areas reached depths of six feet.

1982

(Source: St. Louis Post-Dispatch, 1982)

Up and down the Meramec, the flooded river crested at the highest levels since records have been kept. The river crested at over 40 feet on late Monday, Dec. 6, and early Tuesday. Valley Park, Times Beach, Peerless Park, Pacific, Eureka and other areas of west St. Louis County were afloat.

Employees working in offices on the north side of the large Maritz, Inc., complex in nearby Fenton could look out their windows on Monday, Dec. 6, and watch mobile homes float by. The Maritz headquarters was almost an island, I-44 on one side, the ugly and badly swollen Meramec on the other.

(Source: McGuire, 1982)

Missouri Disaster Response officials estimate that the damage will total $150 million when the grim figures are finally added up. It is estimated that as many as 20,000 people were uprooted from their homes by the storms.

1986

(Source: Dyer, 1993)

In 1986, 32,000 acres of cropland in Cooper County and 24,000 acres in Howard County were affected by flooding that occurred over a period of two weeks in October. On October 6 (the day after the 31.9 crest at Boonville) the Boonville Daily News reported the failure of nearly all the levees between Arrow Rock and Weldon Springs.

1993

(Source: National Oceanic and Atmospheric Administration, 1994)

The Midwest flood of 1993 was an extreme hydrometeorological event and one of the most costly flood disasters in United States history. Initial assessments of the economic damages of the 1993 flood indicated that losses ranged between $15-20 billion (The Great Flood of 1993, Natural Disaster Survey Report, NOAA, February 1994). It caused enormous human suffering and damages to residential, commercial, industrial, agricultural and public properties in large portions of the upper Mis-

sissippi and lower Missouri Rivers and their tributaries. Because of its magnitude, the 1993 flood is quite notable and is unprecedented in many aspects: the areal extent and duration of rainfall and floods, the severity of flooding at many locations, persons displaced, and property damage. Approximately 500 forecast points on major rivers and tributary systems reported stages exceeding flood stage (the water level at which a river goes into flood).

The flood resulted from a combination of many factors. Several federal agencies have carried out systematic studies and analyses of the event. Meteorologic and hydrologic analyses conducted by the National Oceanic and Atmospheric Administrations' (NOAA) Service is summarized as follows:

Meteorological analysis

The flood had its origins in an extended wet period starting 9-10 months prior to the onset of major flooding. This wet period moistened soils to near saturation and raised many stream levels to bank full or flood levels. This set the stage for rapid runoff and record flooding that followed excessive June and July rainfall.

1. Antecedent conditions

In August 1992, wet soil conditions began to appear in the central Great Plains, then increased dramatically by late 1992, encompassing portions of the central, eastern, and southeastern United States. July, September, and especially November 1992 were much wetter than normal over the upper Mississippi River basin; winter precipitation was near normal.

By the March 1993, extremely moist conditions (Palmer Drought Severity Index (PDSI) >4) covered much of Kansas, South Dakota, Iowa, eastern Nebraska, southern Minnesota and Wisconsin, and northern Illinois as a result of the combination of the wet fall and spring snowmelt. This was followed by above-normal precipitation over the upper Mississippi River basin during April and May. Consequently, even before the onset of heavy summer rains, most of the Upper Midwest had saturated soil and well above-normal streamflow.

2. Rainfall patterns during the great flood of 1993

During the summer (June-August 1993), rainfall totals surpassed 12 inches across the eastern Dakotas, southern Minnesota, eastern Nebraska, and most of Wisconsin, Kansas, Iowa, Missouri, Illinois, and Indiana. More than 24 inches of rain fell on central and northeastern Kansas, northern and central Missouri, most of Iowa, southern Minnesota, and southeastern Nebraska, with up to 38.4 inches in eastern central Iowa. These amounts were approximately 200-350 percent of normal from the northern plains southeastward into the central Corn Belt. From the start of the growing season (April 1), precipitation amounts through August 31 were even more impressive: totals approached 48 inches in east-central Iowa, easily surpassing the area's normal annual precipitation of 30-36 inches.

Hydrological analysis

1. Antecedent conditions and hydrologic setting

Since late in the summer of 1992, conditions were wetter than normal over much of the lower Missouri and upper Mississippi River basins. Minor flooding began as far back as December 1992 in some locations as a result of very heavy November rainfall over the upper Mississippi basin. Soils were very wet at the onset of winter. These high moisture levels were locked into the soils as the ground froze.

Although winter precipitation was near normal, with moist antecedent conditions, due in large part to the heavy November rains, flooding began in late March with snowmelt. Because of the frozen ground, and then later because of the moist soils, runoff could not be absorbed by the soils. Rivers in the Dakotas, Minnesota, Nebraska, Iowa, Illinois, Kansas, and Missouri rose rapidly. In late March, the *National Hydrologic Outlook* identified the impacted areas as having "above-average flood potential."

April saw the start of a prolonged period of very wet weather. The period from April through June was the wettest observed in the upper Mississippi basin in the last 99 years. The moisture conditions across the north-central United States on May 1, 1993, can best be described as "saturated."

The extremely wet, cool spring of 1993, coupled with normal to above-normal precipitation in the summer, fall and winter of 1992-93, caused significant spring flooding in the upper Mississippi River basin. Soil moisture conditions, from the surface to a depth of 6 feet, across most of the nine-state region were at "field capacity" (90-100 percent, where 100 percent equals field capacity for any given soil type) by the end of May when values are normally less than capacity.

Review of major flooding

The record-breaking, heavy, late-spring/ summer rainfall amounts and the ensuing record-breaking summer floods evolved from six factors during the spring and summer of 1993. These factors combined in a unique fashion to cause record-high flows on the lower Missouri and portions of the upper Mississippi rivers, as well as on many of their tributaries. On June 1, all conditions in the hydrologic cycle favorable for flooding were present:

1. Persistence of saturated or nearly saturated soils already nearly saturated soils in June became more saturated during the month. By July 1, when typical Midwestern values are 60-70 percent, the plant available moisture values were totally saturated, as reflected by the enormous area that was at 120 percent saturation or higher, across Iowa, much of Missouri, central and northern Illinois, southwestern Wisconsin, and southern Minnesota. Values by August 1 were still abnormally high (50-60 percent is typical), indicating that near saturated soils prevailed in a large, northwest-southeast zone paralleling the upper Mississippi River.

2. High Incidence of Rain Events

A critical factor affecting the record flooding was the near continuous nature of the rainfall. Many locations in the nine-state area experienced rain on 16-22 days in July. This compares to a long term average for July, of 8-9 days with rain. There was measurable rain in parts of the upper Mississippi basin on every day between late June and late July. The persistent, rain-producing weather pattern in the Upper Midwest, often typical in the spring but not summer, sustained the almost daily development of rainfall during much of the summer.

3. Large-Sized Areas

The semi-stationary nature of the convectively unstable frontal conditions across the Upper Midwest from June through early August not only caused the near continuous occurrence of daily rains but also frequently created extensive areas of moderate to heavy rains. Frequently, a day in June or July 1993 would have rain areas that were 100-200 miles wide and 400-600 miles long (typically about 75,000 square miles) across parts of the nine-state area. Most of these rain areas included zones with 1-2 inches of rain over 5,000-15,000 square miles.

4. Orientation of Rain Areas

Several multi-day periods in June and July had large rain areas that were oriented along the major rivers. In late June, several large rain areas were aligned northwest-southeast over the Mississippi River from northern Illinois into central Minnesota. Then, in early July, similar systems became aligned southwest-northwest-southeast over the Mississippi's course from Quincy, Illinois, the southern Wisconsin, at the time the flooding was maximizing in this reach of the river. In early to mid-July, several large rain areas were oriented west-east along the Missouri River and across Missouri. Such alignments deposited enormous amounts of water directly into the main stems of the rivers without any delay for runoff and in-stream storage in the tributaries.

5. Extremely Large Number of Localized Heavy Rains Capable of Producing Flash Floods

Intermixed with the frequent incidence of large areas of moderate to heavy rainfall, as described in (2) and (3) above, were many intense

rainstorms. They are defined here as discrete areas, typically 1,000-5,000 square miles in size, where as much as 6-12 inches of rain falls in 24 hours or less. The isohyetal map of the large July 7 rain, which occurred across central Missouri, contains three such intense 6-inch centers.

6. Seasonal Evapotranspiration Below Normal

The near continuous cloud cover of the June to August period (50 percent of the days were cloudy compared to a normal of 20 percent), coupled with temperatures which were 2-3 degrees below average and a very moist lower atmosphere, reduced actual evapotranspiration to below-normal levels. This reduced the upward movement of moisture from the soil and increased the flood potential.

In summary, the genesis of The Great Flood of 1993 had been set by June 1 with wet antecedent conditions making the Upper Midwest prone to flooding. The water from the ensuing persistent heavy rains of June, July, and August had no place to go other than into the streams and river courses. Record summer rainfall, with amounts achieving 300 to 750-year frequencies thus produced record flooding on the two major rivers, equalling or exceeding flood recurrence intervals of 100 years along major portions of the upper Mississippi and lower Missouri rivers.

1993 Missouri Flood Summary

(Source: SEMA, undated)

* 112 of Missouri's 114 counties were declared disaster areas (Cedar and Dunklin were the only counties not declared)
* There were 49 deaths attributed to the flooding
* An estimated 15,000 to 17,000 Missourians were homeless because of flooding
* 30,000 people were evacuated during the summer flooding
* FEMA estimated that fewer than 22,000 flood insurance policies were in force in designated flood plains where more than 216,000 Missouri households are located.
* Damages totaled about $3 billion
* Agricultural losses were estimated at $1.8 billion
* 3.1 million acres of farmland were either damaged or went unplanted because of 1993 rains
* An estimated 455,000 acres of Missouri River bottom land was destroyed by washouts and sand deposits, with 90,000 acres having deposits greater than 2 feet
* Damage to public and private levees was extensive, 840 of the 1,456 levees were damaged
* More than 280 million sand bags were used
* 250 State highway routes were closed at the same time
* Approximately 950 individual flood sites caused road closures on the State highway system
* All counties except for Camden and Christian reported at least one road closure on the State highway system
* 480 lettered state highway routes experienced road closures
* At one time during the flood the Missouri River could only be crossed in Kansas City, near Rocheport and in St. Louis (22 major bridges were closed at the same time)

1995

(Source: Uhlenbrock, and Holleman, 1995)

The crests of the Missouri and Mississippi Rivers rolled through St. Charles and St. Louis Sunday, leaving behind flooded farm fields and a gouged-out Katy Trail.

This round of flooding caused less damage than the record levels of 1993 because many homes and businesses devastated two years ago have been bought out.

The crests generally were a half-foot lower than expected because floodwater had spilled over most private agricultural levees along the Missouri, spreading into bottom-land farms.

Still, the Flood of 1995 will edge its way into third place, so-far on the all-time list. The Mississippi at St. Louis reached 41.4 feet Sunday afternoon, pushing past the 1844 stage of 41.32 but still shy of the 43.3 feet crest of 1973

and the really big one — nearly 50 feet — of two years ago.

(Source: Manor, 1995)

The flood of 1995 has turned the Port of St. Louis into a marina for hundreds of stranded barges and towboats, and threatens to snarl river transportation around the country.

The Mississippi River was closed from St.Louis, Missouri all the way to Davenport, Iowa

(*Source: Corps of Engineers, authors*).

The Missouri River is closed for the 366 miles from Kansas City to its confluence with the Mississippi. The Illinois River is closed for its 187-mile length.

DROUGHT

INTRODUCTION

In the normal cycles of water availability there are times of moisture surplus and moisture deficit. Drought is a broad term applied to times with moisture deficits. A moisture deficit can be caused by many things. The most commonly mentioned parameter associated with drought is precipitation. Although this is a major factor there are other considerations such as temperature, evapotranspiration, and water being consumed beyond the rate that it is being replenished.

Drought is a complex hydrologic event that can happen anywhere and anytime. There are many things that make it difficult to get a handle on drought. Unlike flooding, drought is something recognizable only after a period of time; neither its start nor finish are distinct. Many factors interact to affect the severity of a drought for any given location. It is difficult to determine drought duration, intensity and extent. In addition, there is no universally accepted definition for drought. An agronomist commonly defines drought seriousness according to soil moisture and the time of its occurrence within the growing season. A meteorologist defines drought in terms of precipitation deficiency. A reservoir operator might be concerned with reservoir inflow, storage and reservoir stage.

Wilhite (1987) incorporated these ways of looking at drought into a system of drought categories. The categories include meteorological drought, hydrologic drought, agriculture drought and socioeconomic drought.

Meteorological drought is related to precipitation deficiencies and the duration of the dry period. A way of expressing meteorological drought is percent of normal precipitation (for a given period).

Agricultural drought is defined by soil moisture deficiencies associated with crop moisture demands. It is related to meteorology, hydrology and agricultural practices. The timing of the precipitation shortage, evapotranspiration amounts, soil type, crop type and developmental stage of the crop are some of the factors that influence agricultural droughts.

Hydrological drought is associated with shortfalls of surface or subsurface water. It is characterized by less than normal streamflow, and reduced lake and groundwater levels.

Socioeconomic drought is related to a deficiency in the supply of water available to meet water demands that provide social or economic good. It has elements of meteorological, hydrological, and agricultural drought.

Although drought is a difficult event to define, it is one of the most important hydrologic conditions to be considered in water planning and management. As a natural disaster its economic, environmental and societal impacts can be widespread and quite significant.

DROUGHT INDICES

Drought indices are an important component in drought monitoring and early warning of impending water shortages. More than 100 drought indices have been developed for designating different types of droughts worldwide. Many of the indices are considered to be useful in detecting drought periods and pro-

viding information about abnormally low water availability and the potential effects of water shortage.

Drought indices vary in their degree of complexity. The U.S. Army Corps of Engineers has suggested that a drought index should help answer two questions: "How rare is the current drought?" and "How likely is it that the current drought will end in the next X months?" The indices described here are the Palmer Drought Severity Index (PDSI), Palmer 'Z' Index (ZNDX), Crop Moisture Index (CMI), Modified Palmer Drought Severity Index (PMDSI), and Surface Water Supply Index (SWSI). These indicies are summarized in Table 5.

The **Palmer Drought Severity Index (PDSI)** is a meteorological drought index developed by Palmer in 1965 to measure the departure of moisture supply from normal levels. The index is based on the concept of the water balance between moisture supply and demand on a monthly or weekly basis. Palmer developed the index to address the intensity and the duration of a drought or wet spell. The aim of the PDSI was to provide a measurement of the severity of drought by computing standardized moisture conditions for different locations and months so that comparisons could be made using the index. The PDSI takes into consideration precipitation, temperature,

Table 5. Summary of drought indices

Drought Index	**Description**
Palmer Drought Severity Index (PDSI)	A meteorological drought index; developed by Palmer to measure the departure of moisture conditions on a monthly or weekly basis; generally varying between -4.0 and +4.0, with negative values indicating dry spells and positive values indicating wet spells.
Palmer Z Index (ZNDX)	Also referred to as Moisture Anomaly Index Z; measuring relative departure of the moisture condition of a particular month and location, from the average moisture conditions of that month; not directly affected by the available moisture supply; useful in assessing the moisture budget of specific months.
Crop Moisture Index (CMI)	Designed to monitor week-to-week crop moisture conditions, based on the mean temperature and total precipitation for each week within a climate division, and the CMI value from the previous week; responding rapidly to changing conditions.
Modified Palmer Drought Severity Index (PMDI)	A modification as an improvement to the PDSI; developed by the National Weather Service, Climate Analysis Center for operational meteorological purposes; incorporating a weighted average of the wet and dry index terms and using a probability as the weighted factor.
Surface Water Supply Index (SWSI)	An index that incorporates both hydrological and climatological features; developed by Shafer and Dezman to complement the PDSI, for moisture conditions across the state of Colorado; an indicator of surface water condition, with snowpack as a major component.

evapotranspiration, and the local Available Water Content (AWC) of the soil and run-off. Human impacts on the water balance, such as new reservoirs, are not included. The computational procedure can be found in the original study by Palmer (1965). When the PDSI is used to evaluate drought or wet conditions in near-real time, it has been referred to as the Palmer Hydrological Drought Index (PHDI). This is because it is based on precipitation, losses, and storage. It does not take into account the long-term trend (Karl and Knight, 1985).

The index varies generally between -4.0 and +4.0, with negative values indicating dry spells, and positive values indicating wet spells. This index may go as high as +8.0 and as low as -8.0 in Missouri.The PDSI is calculated on a monthly basis for climate divisions of the United States. Monthly PDSI values for every Climate Division in the United States are available in the National Climate Data Center (NCDC) from 1895 to the present. Also, PHDI values are calculated for the Climate Divisions and shown in the Weekly Weather and Crop Bulletin.

Table 6. PDSI Classification for wet and dry periods

>=4.00	Extremely wet
3.00 to 3.99	Very wet
2.00 to 2.99	Moderately wet
1.00 to 1.99	Slightly wet
0.50 to 0.99	Incipient wet spell
0.49 to -0.49	Near normal
-0.50 to -0.99	Incipient drought
-1.00 to -1.99	Mild drought
-2.00 to -.2.99	Moderate drought
-.3.00 to -3.99	Severe drought
<=-4.00	Extreme drought

The effectiveness and applications of the PDSI have been examined and described in many articles. There are considerable limitations and sensitivities of the method, described in detailed by Alley (1984) and Karl and Knight (1985). The major limitations include: that (1) the beginning and end of a drought or wet spell were arbitrarily selected based on Palmer's study of central Iowa and western Kansas and have little scientific meaning; (2) all precipitation is treated as rain (i.e. snowfall, snow cover, and frozen ground are not included in the index so that the timing of PDSI values may be inaccurate in the winter and spring months in region where snow occurs); (3) the PDSI is sensitive to the Available Water Content (AWC) of a soil type (i.e. applying the index for a climate division may be too general); (4) the two soil layers within the water balance computations are simplified and may not be accurately representative for a location; (5) the natural lag between when precipitation falls and the resulting runoff is not considered; and (6) the method used to estimate potential evapotranspiration is only an approximation.

The **Palmer 'Z' Index (ZNDX)** was developed by W.C. Palmer (1965) to measure a moisture departure from climatically normal conditions for that month. It is sometimes referred to as Moisture Anomaly Index Z. It has been described as an index that denotes the relative departure of the moisture conditions of a particular month and location, from the

Table 7. ZNDX classification for wet and dry periods

>3.50	Extreme wetness
2.50 to 3.49	Severe wetness
1.00 to 2.49	Mild to moderate wetness
-1.24 to 0.99	Near normal
-1.99 to -1.25	Mild to moderate drought
-2.74 to -2.00	Severe drought
<-2.75	Extreme drought

average moisture conditions of that month (Alley, 1984). The most important difference between the ZNDX and the PDSI is the duration of a drought (or wet spell). While the objective of the ZNDX is to measure the moisture abnormality for a given month, the PDSI measures the moisture abnormality over a period of dry, wet, or near-normal weather that may span many months. Since the ZNDX is not directly affected by the available moisture supply through stored soil moisture, it is useful in assessing the moisture budget of specific months (Karl and Quayle, 1981).

Palmer assigned the Z classification scale (Table 7) of the drought severity value based on his two original study areas in central Iowa and western Kansas. This index can respond to above-normal monthly precipitation, even during drought periods. The ZNDX is also generated for the climate divisions in the United States, and the long-term archive of the record is through 1895 to present and updated monthly.

The **Crop Moisture Index (CMI)** is another commonly used drought severity index, developed by Palmer (1968) from procedures within the calculation of the PDSI. It is published jointly on a regular basis by the National Oceanic and Atmospheric Administration (NOAA) and the U.S. Department of Agriculture (USDA). The CMI uses a meteorological approach to monitor week-to-week conditions, based on the mean temperature and total precipitation for each week within a climate division, as well as the CMI value from the previous week. It responds rapidly to changing conditions, and is weighted by location and time. The map of the CMI displays the weekly values of CMI across the United States, and can be used to compare moisture conditions at different locations. The CMI is effective for evaluating short-term moisture conditions across major crop producing regions whereas the PDSI detects long-term wet and dry spells.

The **Modified Palmer Drought Severity Index (PMDI)** was developed by the National Weather Service, Climate Analysis Center, for operational meteorological purposes. They made this modification as an improvement to the PDSI. The modification (PMDI) incorporates a weighted average of the wet and dry index terms, using a probability as the weighted factor. The Palmer drought Program, at the Climate Analysis Center, calculates three intermediate parallel index values each month. Only one value is selected as the PDSI drought index for the month. This selection is made internally by the program on the basis of probabilities. If the probability that a drought has ended is 100%, the third index is assigned to the PDSI. A detailed discussion can be found in "A review of the Palmer Drought Severity Index and Where do we go from here?", (*Proceedings of the Seventh Conference on Applied Climatology*, pp. 242-246, American Meteorological Society, Boston, Massachusetts).

The **Surface Water Supply Index (SWSI)** was developed by Shafer and Dezman (1982) to complement the Palmer Drought Severe Index (PDSI) for moisture conditions across the State of Colorado. The PDSI does not account for snow accumulation and subsequent runoff; it is generally applied for relatively homogeneous regions. Shafer and Dezman designed the SWSI to be an indicator of surface water conditions, with snowpack as a major component.

The objective of the SWSI was to incorporate both hydrological and climatological features into a single index value resembling the PDSI for each major river basin in the State of Colorado. These values would be standardized to allow comparisons between basins.

Inputs required by the SWSI include snowpack, streamflow, precipitation, and reservoir storage. The SWSI is a season-dependent index. The SWSI is computed with snowpack, precipitation, and reservoir storage in the winter. During summer months, streamflow replaces snowpack as a component within the SWSI equation.

The SWSI, along with the PDSI, has been used to trigger the activation and deactivation of the Colorado Drought Plan. One advantage is that it is simple to calculate and gives a representative measurement of surface water supplies across the state. It has been modified

and applied in other western states as well. These states include Oregon, Montana, Idaho, and Utah.

There are some limitations in the application and computation of the SWSI. If any station is discontinued, new stations need to be added to the system and new frequency distributions need to be determined for that component. As changes in the water management within a basin occur, such as flow diversions or building new reservoirs, the entire SWSI calculation for that basin needs to be recalculated to account for changes in the weighting of each component. Also, if an extreme event occurs that is beyond the historical time series, the index would need to be re-evaluated to include that event within the frequency distribution of a basin component.

MODELING DROUGHT

The water balance equation (also referred to as water budget) is a basic tool in performing hydrologic modeling of drought. The hydrologic approach has been widely used to estimate water availability for water-planning and drought study purposes.

The water balance model employs a continuity equation and can be applied to any scale, from continental land masses, to pond design, to a small crop field or even individual plants. The basic form of the water balance can be expressed as :

Inflow - Outflow = Change of Storage

Specific parameters make up each component. The same component can be in-flow in one system but out-flow in another depending on the system of interest. For example, springs are in-flow in a surface water system, but out-flow in a groundwater system.

In doing water balance modeling, the various parameters that make up the components of the water balance must be estimated. Common parameters include precipitation, runoff, evaporation, transpiration and infiltration. Appendix 2 describes water balance parameters and sources of information.

When modeling drought, it is critical to use numbers representative of drought periods. Using average numbers can result in gross errors. This applies whether you are inputting precipitation, evaporation, water use or almost any other parameter.

From the water balance we can estimate the effects of water use during drought on the water system (i.e., drawdown of a reservoir or aquifer). It also allows us to estimate with some level of assurance the water that a water system yields. Some of the common terms used in surface water availability studies are firm yield and safe yield. Firm yield is commonly considered the amount of water available, using the worst drought on record. For development of aquifers a common term is safe yield. Safe yield is the amount of water that can be removed from an aquifer without depleting it. Firm yield and safe yield are critical components in designing water supply systems. They determine the bottom line of water availability during drought conditions.

DROUGHT SUSCEPTIBILITY - WATER AVAILABILITY

As described in an earlier section, drought has many definitions. Drought susceptibility is a product of the amount of water available and the amount of water needed for specific water uses. The following discussion provides regional overviews of water availability. A more detailed discussion can be found in the Surface Water and Groundwater Volumes of this series.

NORTHERN AND WEST-CENTRAL MISSOURI

The northern half of Missouri is generally characterized by poor groundwater availability and thus is more dependent on surface water. Base flow in the streams is dependent on rainfall. Consequently, impoundments are built to store water.

Large federal reservoirs managed by the U.S. Army Corps of Engineers are located on the Chariton (Rathbun), Little Chariton (Long Branch), Little Platte (Smithville), and Salt rivers (Mark Twain). Rathbun Lake releases water into the Chariton River, which flows into

Missouri but is located across the state line in Iowa. These large reservoirs are a reliable source of water. Table 8 provides storage capacity for these reservoirs.

Smaller impoundments dot the landscape and supply water for agricultural, domestic and industrial use. Many of these small impoundments experience problems during drought periods, when there can be extended periods with very little runoff.

In northern Missouri glacial deposits overlie the older consolidated rocks. This extends south of the Missouri River in the western part of the state and swings north to approximate the course of the river on the eastern part. These glacial deposits locally contain sand and gravel deposits that are tapped to supply water. Many of these deposits supply sufficient amounts of water during normal weather for domestic and some municipal use. During

Table 8. Multi-purpose storage in Corps Reservoirs. Approximate storage capacity in acre-feet

Reservoir	Total Capacity	Multi-purposes	Conservation/Dead
Wappapello[1]	613,000	——	31,000
Clearwater[1]	413,000	——	22,000
Norfork[1]	1,983,000	707,000	544,000
Bull Shoals[1]	5,408,000	2,084,000	964,000
Table Rock[1]	3,462,000	1,942,000	760,000
Stockton[1]	1,674,000	875,000	25,000
Pomme de Terre[2]	644,000	237,000	——
Harry S Truman[2]	5,209,000	1,203,000	244,000
Longview[1]	46,900	20,600*	——
Blue Springs[1]	26,950	10,850*	——
Smithville[1]	246,000	102,200	52,300
Long Branch[1]	65,000	36,000*	——
Mark Twain[1]	1,428,000	457,000	87,000**
*Includes sediment		**Inactive storage	

[1]Source: Corps, 1995, Water Resources Development by the U.S. Army Corps of Engineers in Missouri.
[2]Source: Corps, undated, Summary of Engineering Data—Lower Missouri River Basin Projects.

drought periods, when little or no recharge occurs, shortfalls in water availability can occur. There are larger deposits of sand and gravel in pre-glacial alluvial valleys that are buried under glacial deposits. These deposits contain large quantities of water, which are not as prone to drought. Groundwater is described further in Appendix 2.

THE MISSOURI AND MISSISSIPPI RIVER SYSTEM

The Missouri and Mississippi rivers are part of a large inland waterway system for transporting commodities. This system links the nation's heartland with international markets. This same system provides many beneficial water uses beyond commercial navigation. These include recreation, water supply and aquatic habitat. Missouri, along with many other states, is highly dependent on the Missouri and Mississippi river systems to provide water for these uses.

The Missouri and Mississippi river systems are appreciably different in the way that they are managed for drought. The Missouri River system has large reservoirs that can store large amounts of water. Much of this storage capacity is contained in six main-stem reservoirs located in Montana, North Dakota, South Dakota and Nebraska. Excluding storage capacity that is exclusively reserved for flood control, these reservoirs have a storage capacity of about 68.8 million acre-ft (MAF). These reservoirs were designed to support downstream water needs under the drought conditions of the 1930s. Since the completion of the Missouri River main stem reservoirs, this system has not been tested by an extreme, long-term drought.

Normally there is ample water flowing in the Missouri River to support consumptive uses. However, during low flow periods there can be problems maintaining access to the water. Public water systems have created some inventive ways to combat some of these problems. For example, putting the intake on a float or movable cart. This problem has been most prevalent during winter months when ice causes a damming impact upstream, and dramatically reduces flow. Groundwater is also readily available in the Missouri River alluvium as a source of relatively high-quality water to meet water supply needs.

Low flow has impacted non-consumptive uses of the Missouri River in recent years. During the 1988 to 1992 drought in the Missouri River Basin, releases from the large Missouri River reservoirs were inadequate to maintain normal commodity shipments on the river. Barges were loaded lighter to reduce draft so that they could operate in shallower water. Season length for movement of commodities was also reduced. Low flow does not affect just commodity shipments. It can also have a negative affect on fish. Low flow can diminish important fish habitat, leading to increased fish mortality and poor reproduction.

The Mississippi River does not have a big system of reservoirs to supply water during drought. As part of the inland waterway system, the Mississippi River upstream from St. Louis has a series of low-head dams which maintain water depth in the channel. The dams do not impound much water although some do serve as run-of-river hydropower facilities. These low-head dams maintain water depth by creating a series of pools. Each dam is equipped with a lock system that allows barges and boat traffic to pass from one pool to the next in a stair step fashion (figure 20).

Lock 27, in the Chain of Rocks Canal just east of St. Louis, is the last downstream lock on the Mississippi. From this point downstream, the Mississippi River is free flowing. It is dependent on adequate flow, with the help of dredging, dikes and bank stabilization, to provide deep enough water for navigation.

The U.S. Army Corps of Engineers estimate that navigation on the Mississippi would be inhibited, downstream of the lock and dam system, if the stage fell below 2 feet at St. Louis (about 90,000 cfs); and would cease entirely at a stage of -4.5 feet (about 44,000 cfs) (COE, 1994).

The reach between Lock 27 and the mouth of the Ohio River has been a critical reach that has impacted navigation traffic. The large impoundments in the Missouri River System makes this reach less susceptable to low flow impacts than if the large reservoirs did not exist.

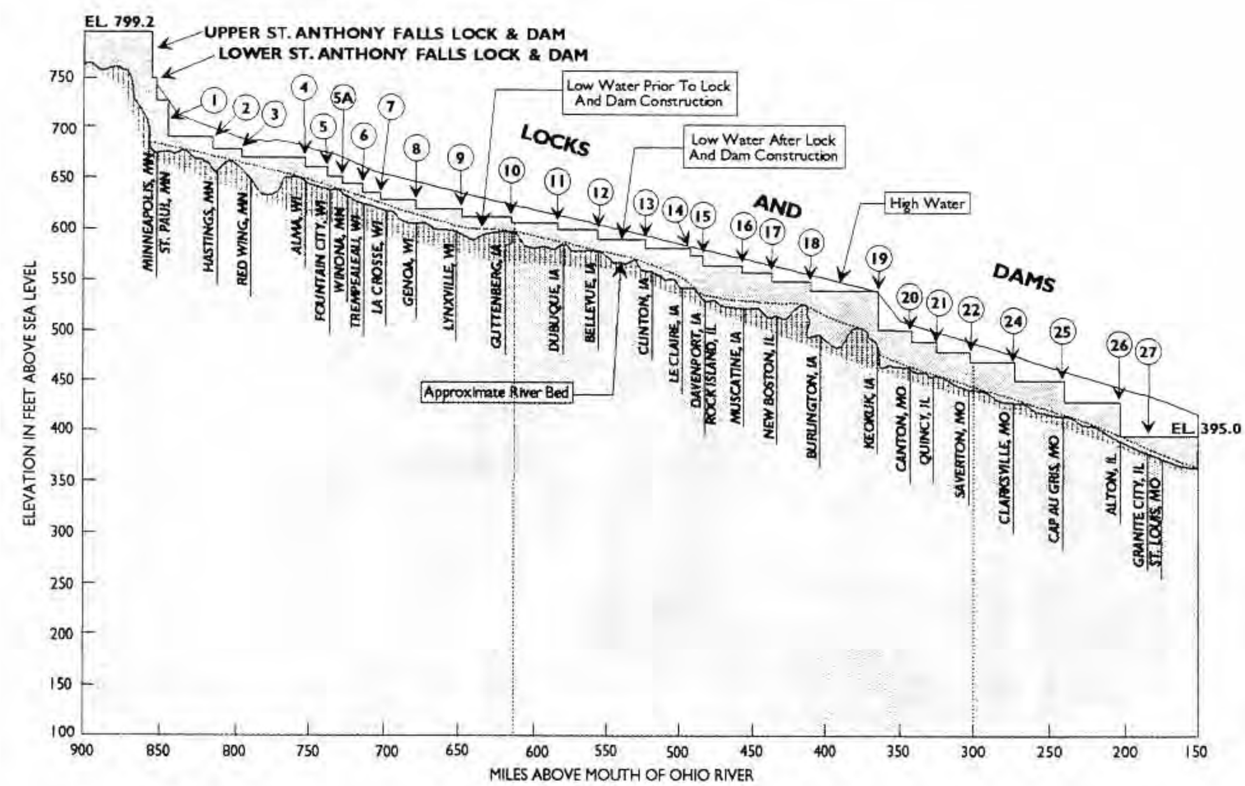


Figure 20. Mississippi River locks and dams (source: U.S. Army Corps of Engineers).

Under many flow conditions, the flow from the upper Mississippi River is greater than that from the Missouri River. However during dry times, contributions from the Missouri River can make up a substantial portion of the flow in the Mississippi River. During October of 1988, when the Mississippi River at St. Louis was as low as 56,200 cfs, the Missouri River was flowing at a rate exceeding 45,000 cfs.

Downstream of the Ohio River, water availability on the Mississippi River has not been as problematic as on upstream reaches. The flow at this point is made up of contributions from many river systems including the upper Mississippi River, Missouri River, and Ohio River. The combined drainage area is over 900,000 square miles (about 73% of the total drainage area for the entire Mississippi River Basin).

The long-term average discharge at the U.S. Geologic Survey gaging station on the Mississippi River at Memphis, Tennessee, is 485,000 cfs. This is more than two and a half times the long-term average discharge at St. Louis. Even with this large drainage area, occasional low flows have occurred downstream of the Ohio River. The minimum daily discharge at Memphis is 79,200 cfs, which occurred August 26, 1936. The Mississippi River at St. Louis was flowing at about 40,000 cfs during that period. With flow being typically higher than river reaches upstream of the Ohio River, the channel is much larger. The Corps estimates that flows less than 189,000 cfs at Cairo, Illinois, would restrict navigation. At flows lower than 80,500 cfs, all navigation would halt.

OZARKS

Streams and rivers in the Ozarks are commonly fed by springs. Many of these springs maintain a discharge even during pe-

riods of drought. There are several large reservoirs which are capable of storing large amounts of water. Truman, Lake of the Ozarks, Stockton, and Pomme de Terre lakes are located in the Osage River Basin; Table Rock, Bull Shoals, and Norfork lakes are located in the White River Basin; and Clearwater and Wappapello lakes are located in the Black River Basin. Table 8 lists federal reservoirs and their storage capacity.

The bedrock aquifers of the Ozark region of Missouri, including the Springfield Plateau in the southwest part of the state, and the Salem Plateau in the southeastern and southcentral part of the state, contain large quantities of groundwater. There are several water-bearing bedrock formations that are capable of supplying municipal or industrial needs. These formations are Cambrian- and Ordovician-age dolomites and sandstones. In southwestern and western Missouri they are overlain by Mississippian limestone. The aquifers are discussed further in Appendix 2.

Southeast Missouri (Bootheel)

Since the Bootheel region receives the largest amount of precipitation in the state, is bordered by the Mississippi River, has an aquifer system replenished by the Mississippi River and streams from the Ozarks, water supply is ample even in drought. Large groundwater withdrawals from major industrial and municipal wells, however, do affect the shallow water table within the vicinity of the wells. This in turn causes small wells to have production problems.

DROUGHT SUSCEPTIBILITY - WATER USE

The primary emphasis in this volume is on the hydrologic components of flood and drought. In coping with drought it is also important to consider the use that is impacted. Different uses are affected differently. This is a crucial point, whether planning for drought or assessing conditions. The time of the year and available soil moisture may be extremely important to someone growing crops. Groundwater or water stored in reservoirs might be important to the operation of a domestic or municipal water supply. Still other consumers might be more dependent on the depth, velocity and other characteristics of the water in a river or a lake; such as commercial navigation or fisheries. The following discussion provides a brief overview of water use relative to drought. More comprehensive descriptions of water use can be found in *Volume IV, Water Use of Missouri,* in this series.

Agriculture

Agriculture is impacted by a lack of precipitation. Although all areas of the state experience periods with less than normal precipitation, some regions are more prone to agricultural drought than others. Drought susceptibility can be greatly influenced by land management practices, soil type, slope and other watershed characteristics. The type of agricultural enterprise needing the water is also a factor.

Livestock grazing is not as vulnerable as crops to short durations without rainfall. It takes a prolonged period deficient in rainfall to seriously damage grazing conditions and livestock water sources. However, after pasture conditions deteriorate, it will require significant amounts of rain for conditions to recover. It can also take a long period for water supplies to recover; although runoff from short-duration, intense rainstorms, can partially refill ponds without appreciably improving soil moisture conditions.

Crops can be severely impacted over much shorter periods of deficient soil moisture. This is especially true during certain stages of the growing cycle. The impact of drought on crops can be greatly reduced with the use of irrigation.

Irrigation is employed in some regions of the state more than others, due in part to water availability. Much of the irrigation that does occur in Missouri uses groundwater, where it is economically feasible to drill and pump the water from irrigation wells. Such wells are common in the Bootheel where relatively shallow groundwater supplies produce large quantities of water at low cost. Increased well

development costs and more mineralized water quality limit the amount of irrigation in other parts of Missouri. For irrigation to be economically feasible a combination of suitable soils, topography, market conditions, available financing, and management capabilities must all come together for long-term success. Figure 21 shows the statewide irrigation distribution, based on the Missouri Major Water Users Database (source: *State Water Plan, Volume IV, Water Use of Missouri*).

WATER SUPPLY

Domestic and municipal water use commonly depends on stored water, either in reservoirs or groundwater, although some communities have very little water storage and depend on flowing water. Surface water supplies are very dependent on the timing and volume of runoff. Groundwater recharge is dependent on precipitation and infiltration. Most of the aquifers used for domestic and municipal water supply are not dramatically

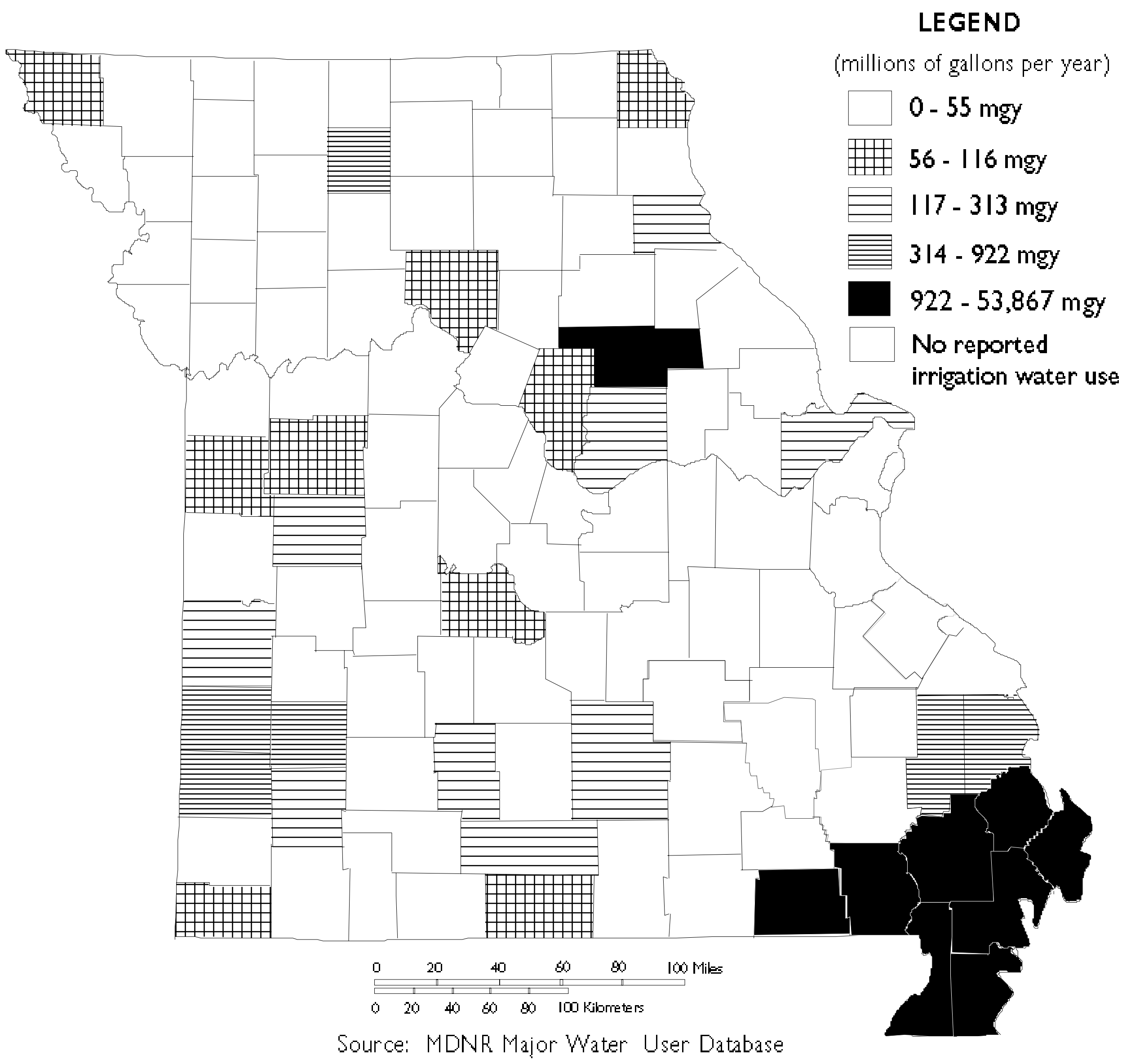


Figure 21. Irrigation water use in Missouri, 1993.

affected by week to week moisture conditions.

Missouri has seen a transition from large numbers of self-supply users, to increased public water supply. By pooling resources Missourians have developed public water supplies that are more reliable and less prone to drought for the population at large. Even so, some of these systems, especially small ones, are still drought prone. Larger regional water supplies may help alleviate some of the problems of drought. For example, the Clarence Cannon Wholesale Water District is a recently formed regional supply that serves several counties surrounding Mark Twain Lake in Monroe and Ralls counties. Because of its large drainage area and ample storage, the lake provides a very dependable supply of water, even in drought.

Fisheries

During drought we are usually interested in the amount of water that can be captured for consumption. Fish and other aquatic organisms are dependent on aquatic habitat and the water left in lakes, rivers and streams. Aquatic habitat is determined by the chemical, biological and physical characteristics of a water system. Seasonal and other variations among these parameters are natural and generally improve habitat. As drought conditions worsen, however, habitat can deteriorate to critical levels and fish populations may suffer. This is especially true in an already stressed system.

To assess the impacts of drought conditions on fish, the quantity of water alone is not enough. Chemical, biological and physical parameters must be considered including the amount of dissolved oxygen, species composition and temperature. Detailed studies can tell us the threshold where certain species will be affected, and the quantity of water necessary to support critical habitat.

OVERVIEW OF DROUGHTS - ANALYTICAL AND HISTORICAL

A historical view of drought should combine scientific and historical investigative approaches. The following discussions provide overviews from both these perspectives.

Analytical Perspective - Palmer Drought Severity Index (PDSI)

The Palmer Drought Severity Index is a useful tool for comparing long term trends in moisture conditions from a hydrological perspective. Because drought impacts are related to many factors, including economic, physical and agricultural stress from pests, it should be kept in mind that this analysis is limited to hydrological severity of drought based solely on the PDSI.

The monthly Palmer Drought Severity Index (PDSI) is available at the National Climate Data Center (NCDC) from 1895 to 1994 for every region in the United States. The data used in this discussion was downloaded from the internet from the National Climate Data Center (NCDC).

The historic PDSI were analyzed to determine how often varying degrees of dryness occurred during this 100-year period. Accumulative frequencies (how often a PDSI was less than or equal to a particular index), are displayed in figures 21 through 27. Selected values from this analysis are listed in Table 9.

From this table we see that in Region 1, an extreme drought (PDSI less than or equal to -4), occurred 5.4 percent of the time. A severe to extreme drought (PDSI less than or equal to -3) occurred 12.1 percent of the time. In Region 6, a PDSI less than or equal to -4 occurred only 2.5 percent of the time, and a PDSI less than or equal to -3 occurred 7 percent of the time. According to these PDSIs, severe and extreme drought are more common in Region 1 than Region 6.

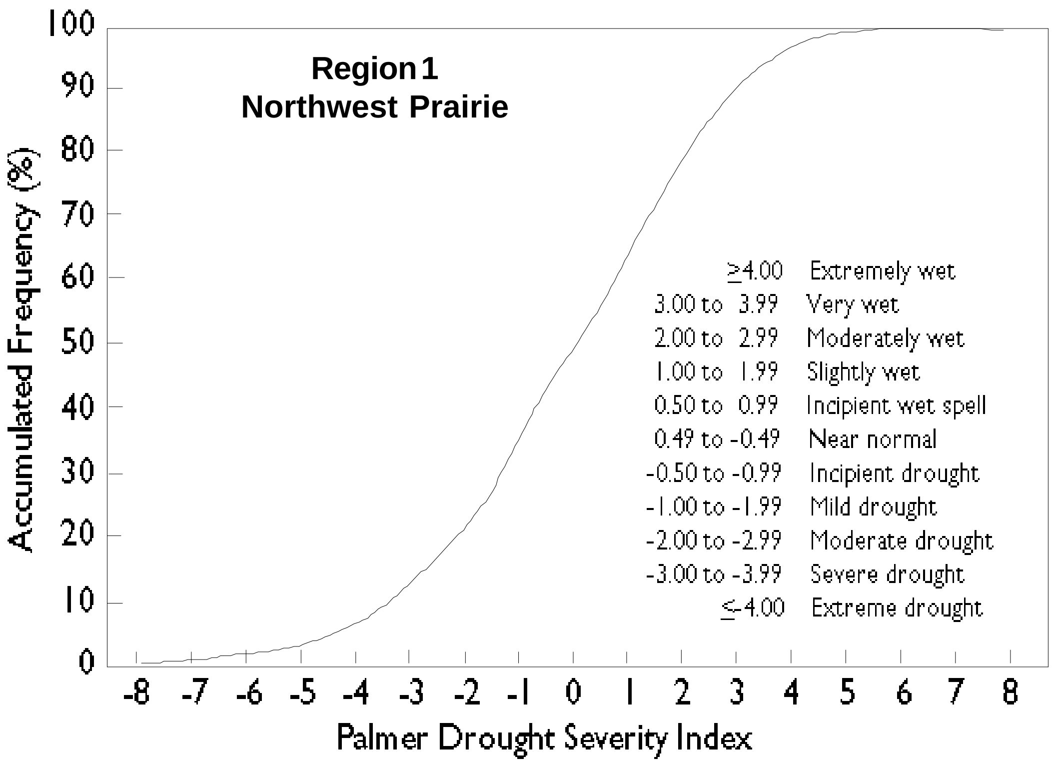


Figure 22. Palmer Drought Severity Index accumulated frequency, Region 1 (Northwest Prairie), Monthly Data 1895-1994 (percent less than or equal to).

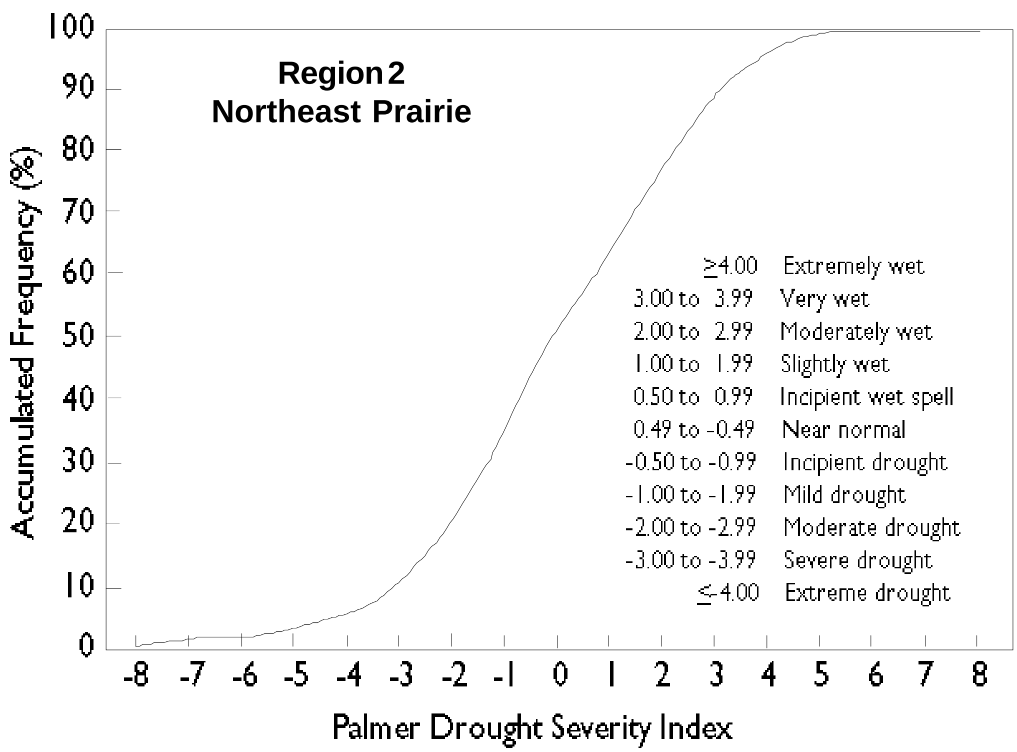


Figure 23. Palmer Drought Severity Index accumulated frequency, Region 2 (Northeast Prairie), Monthly Data 1895-1994 (percent less than or equal to).

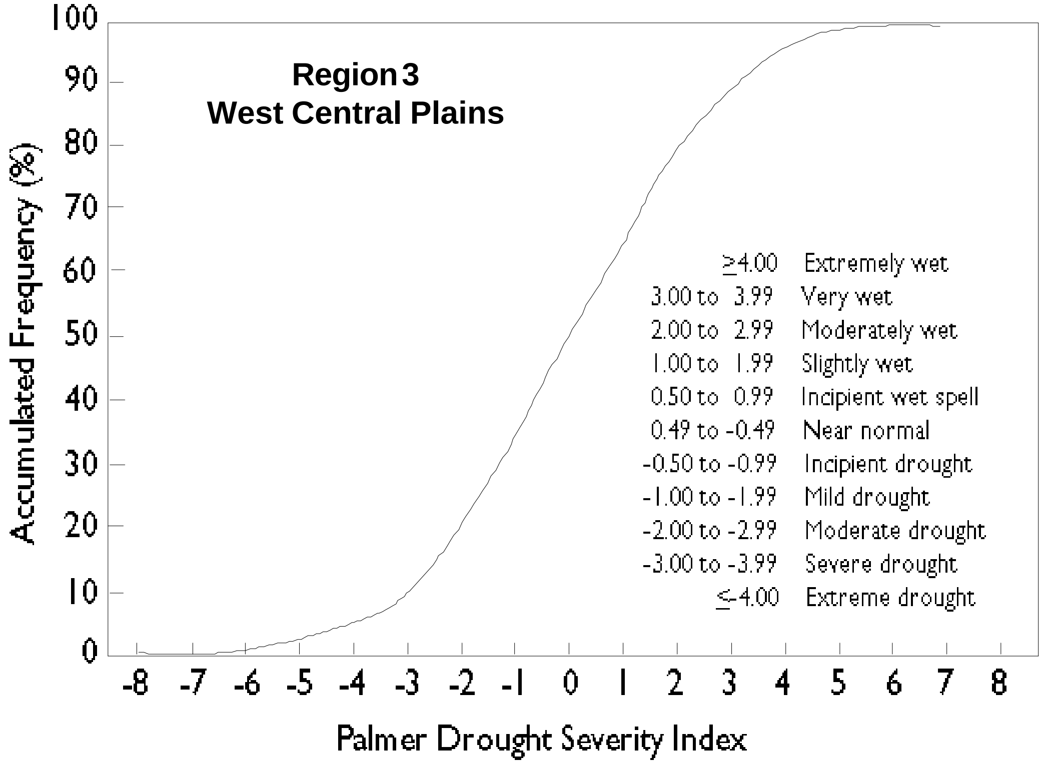


Figure 24. Palmer Drought Severity Index accumulated frequency, Region 3 (West Central Plains), Monthly Data 1895-1994 (percent less than or equal to).

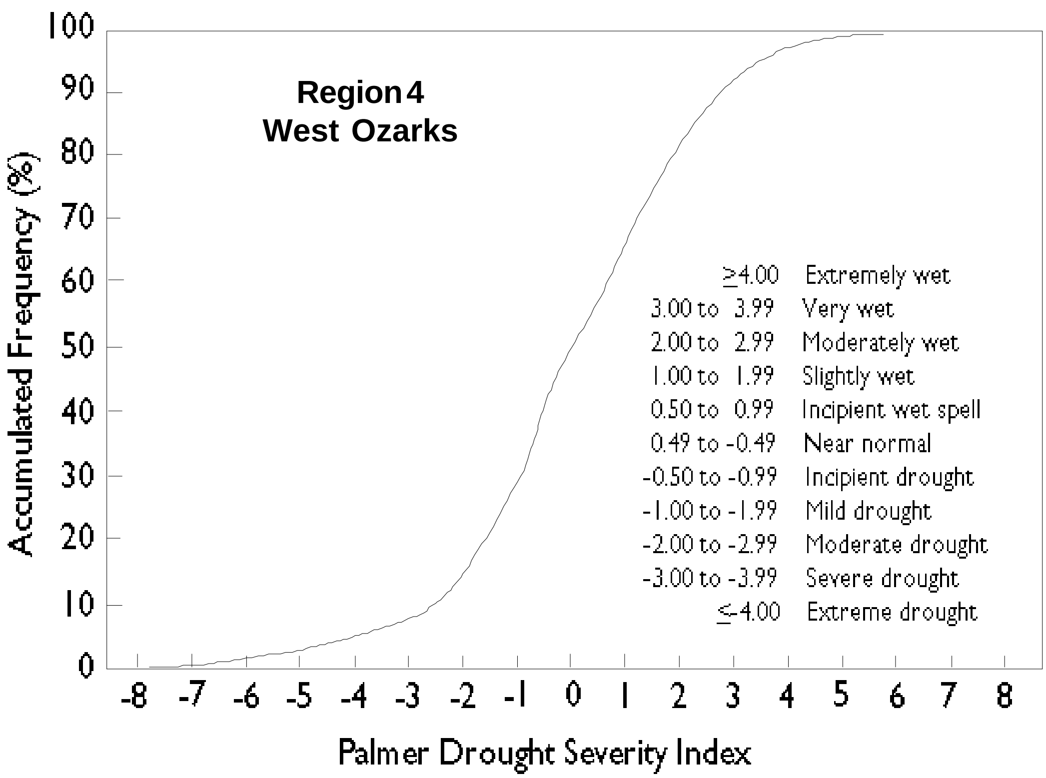


Figure 25. Palmer Drought Severity Index accumulated frequency, Region 4 (West Ozarks), Monthly Data 1895-1994 (percent less than or equal to).

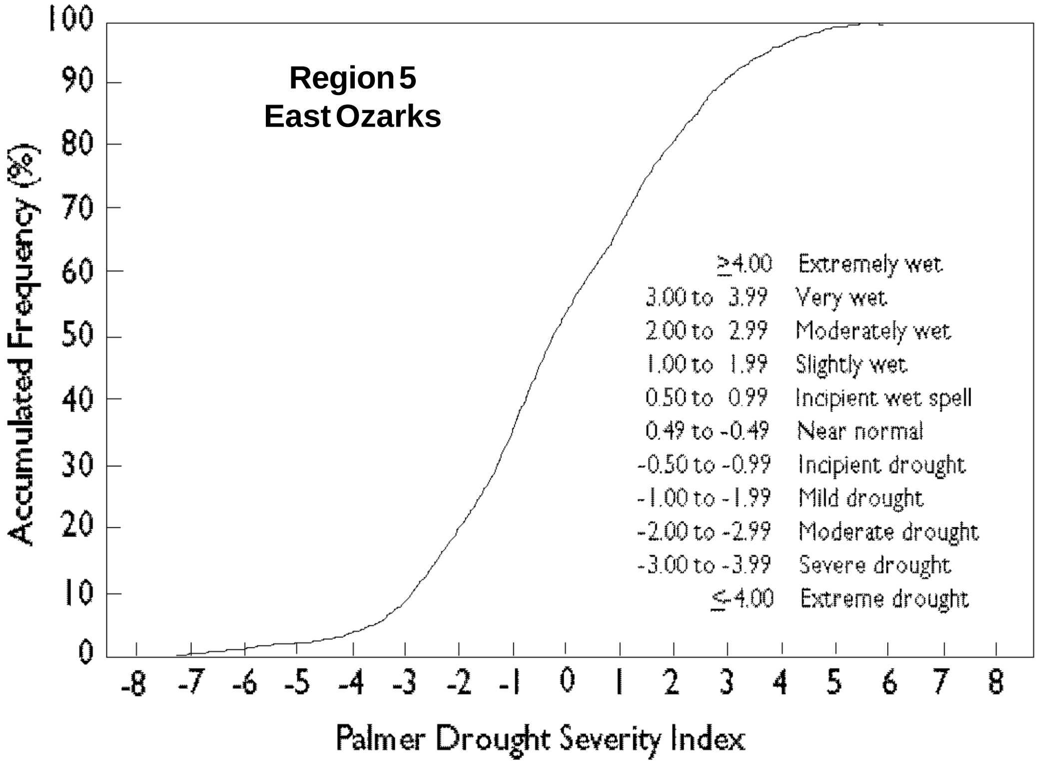


Figure 26. Palmer Drought Severity Index accumulated frequency, Region 5 (East Ozarks), Monthly Data 1895-1994 (percent less than or equal to).

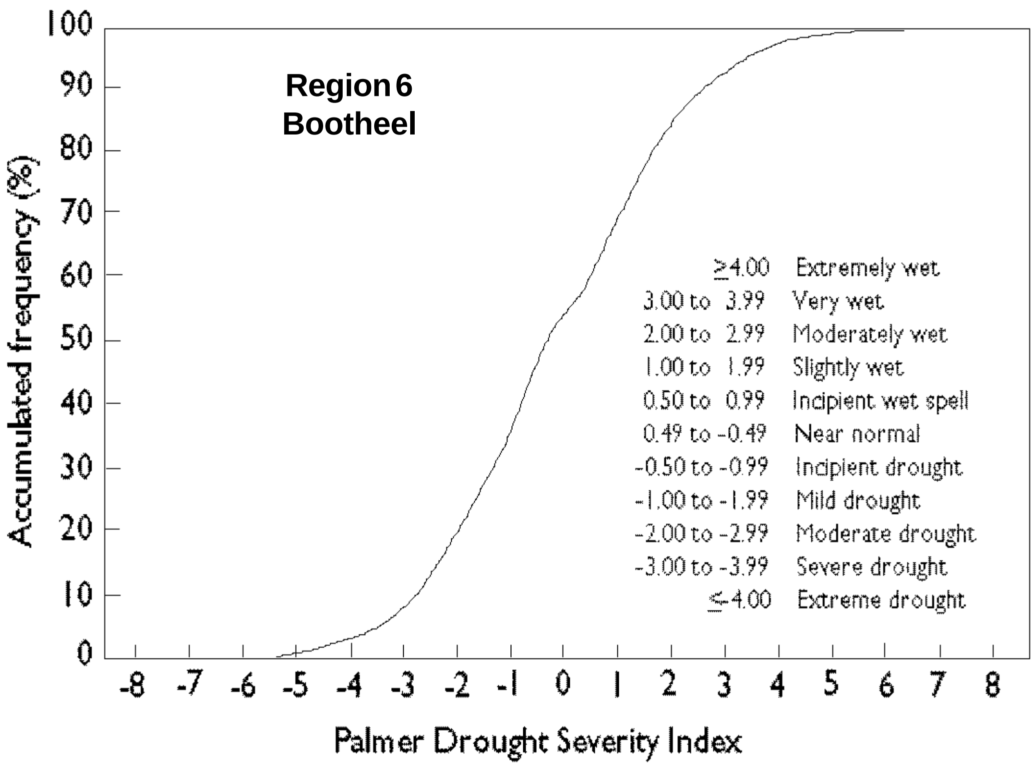


Figure 27. Palmer Drought Severity Index accumulated frequency, Region 6 (Bootheel), Monthly Data 1895-1994 (percent less than or equal to).

Table 9. Palmer Drought Severity Index accumulated frequency, percent less than or equal to (Monthly Data 1895-1994).

PDSI	Region 1	Region 2	Region 3	Region 4	Region 5	Region 6
-8	0.0	0.2	0.0	0.1	0.0	0.0
-7	0.2	0.6	0.2	0.8	0.4	0.0
-6	1.0	1.1	0.8	1.4	0.9	0.0
-5	2.3	2.5	2.1	2.5	1.5	0.9
-4	5.4	4.9	4.2	5.0	2.9	2.5
-3	12.1	10.6	9.5	7.5	8.3	7.0
-2	19.2	19.3	20.4	15.4	18.8	18.8
-1	32.7	32.9	34.2	29.8	34.7	33.5
0	49.4	50.3	50.2	50.3	52.5	54.0
1	63.9	61.8	63.8	67.2	65.3	66.5
2	77.0	75.5	78.1	81.5	79.3	82.8
3	88.2	88.3	88.9	92.0	90.0	92.1
4	95.7	95.7	95.9	98.2	96.0	97.3
5	98.8	98.8	99.1	99.6	99.4	99.3
6	99.5	99.6	99.8	99.9	100.0	99.8
7	99.7	99.8	100.0	100.0	100.0	100.0
8	99.9	100.0	100.0	100.0	100.0	100.0

The monthly PDSI data can also be examined with regard to specific periods. Figures 28-34 show the average annual PDSI from 1896 to 1994. On a statewide basis, the number of consecutive years of extreme drought (PDSI$\leq$-4) is very small (figure 28). In the 1950s however, the state experienced intense drought as reflected in the very low PDSI. In Region 1 (figure 29), a severe to extreme drought developed and persisted from 1954 to 1957. A notable extreme wet spell (PDSI = 5.5) occurred in 1993. There were several severe wet spells (PDSI$\geq$3) during the years 1927 to 1929, 1973 and 1982. Figure 30 shows that in Region 2 the most intense drought spell was in 1954 and the most intense wet condition in 1993. Figure 31 and 32 depict the conditions of Regions 3 and 4. The wet and dry characteristics were quite similar in these two regions, with extreme drought in the 1950s and severe to extreme wet condition in 1993 to 1994. In Region 5, an extreme drought developed in the 1950s (figure 33). In 1993 when most of the state was extremely wet, Regions 5 and 6 were not as extreme. There were numerous other years that were severe to extremely wet in these regions. Region 6 started the prolonged drought spell in the 1950s one year earlier than rest of five regions, and ended one to two years earlier than the other regions (figure 34).

Notice that when an extreme drought occurred over more than half of the nation in 1930's, the PDSI in Missouri did not fall into an extended period of extreme drought. The drought indices appear to be rather normal (except in Region 1 and Region 2, which have one year of severe drought). While the drought of 1988-1989 was recognized as one of the most severe that has occurred in the Mississippi River Basin, the two years are normal to moderate with respect to PDSI within the state. Region 6 was even in a wet spell during 1988 and 1989.

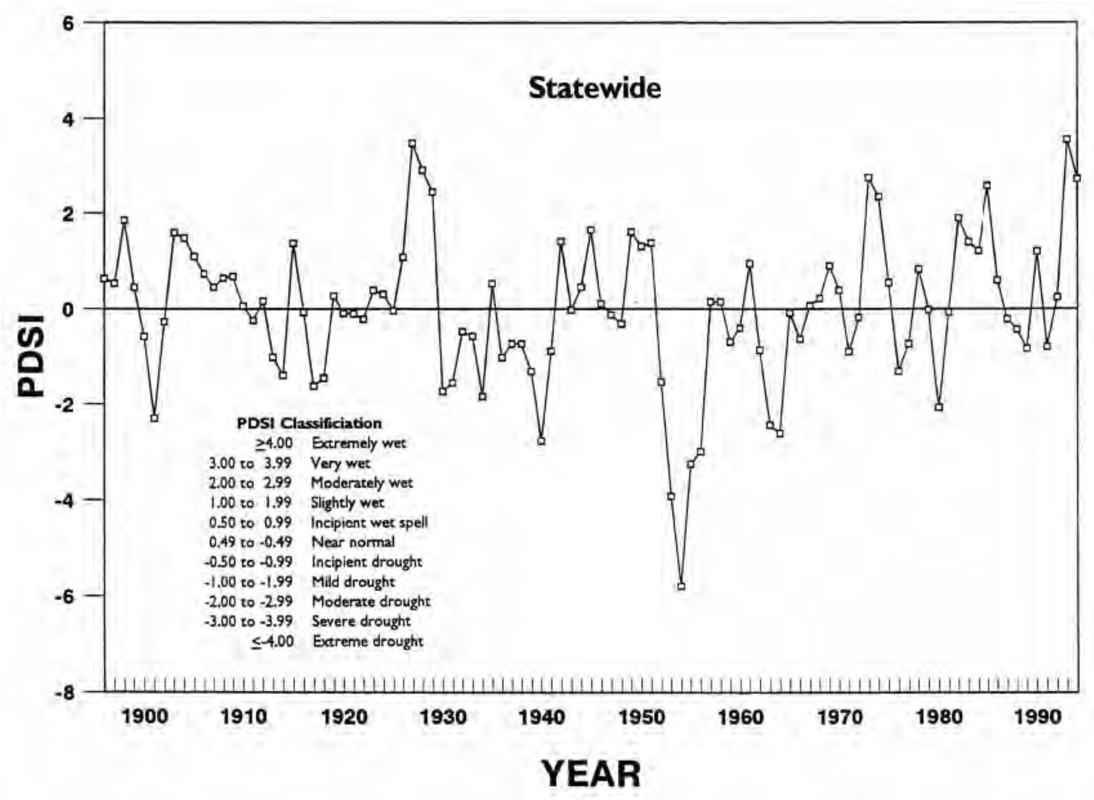


Figure 28. Average annual Palmer Drought Serverity Index - Statewide.

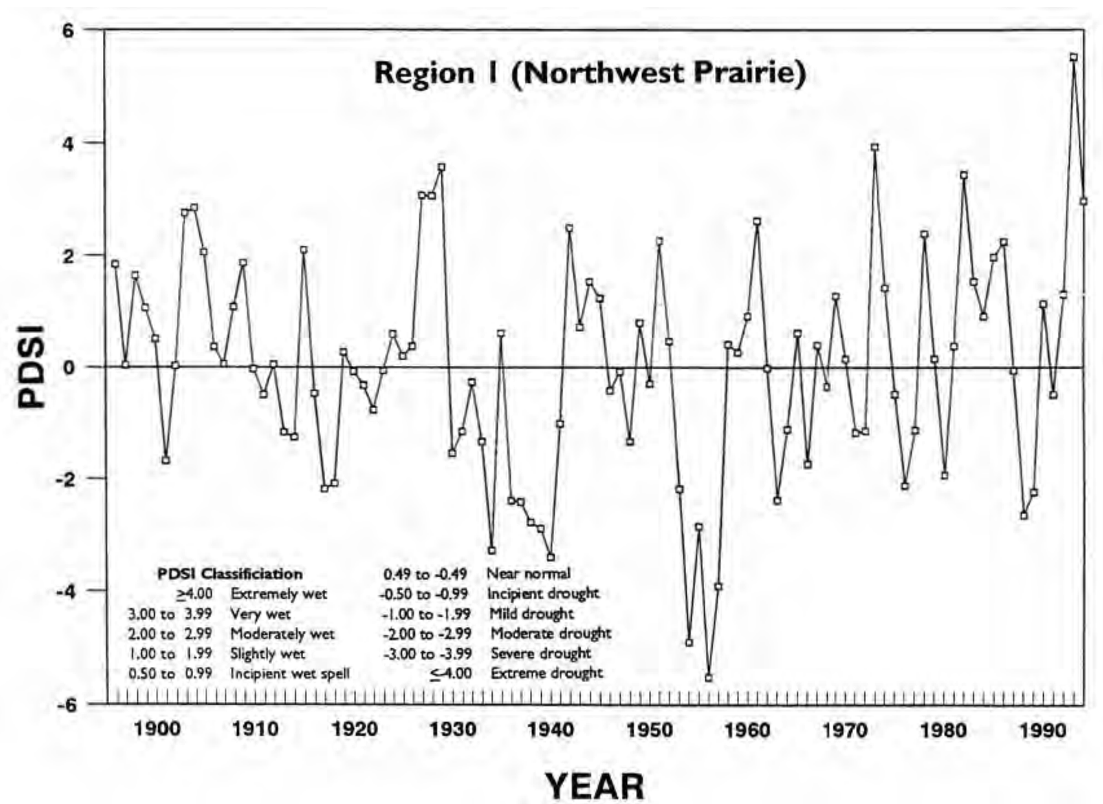


Figure 29. Average annual Palmer Drought Serverity Index - Northwest Prairie.

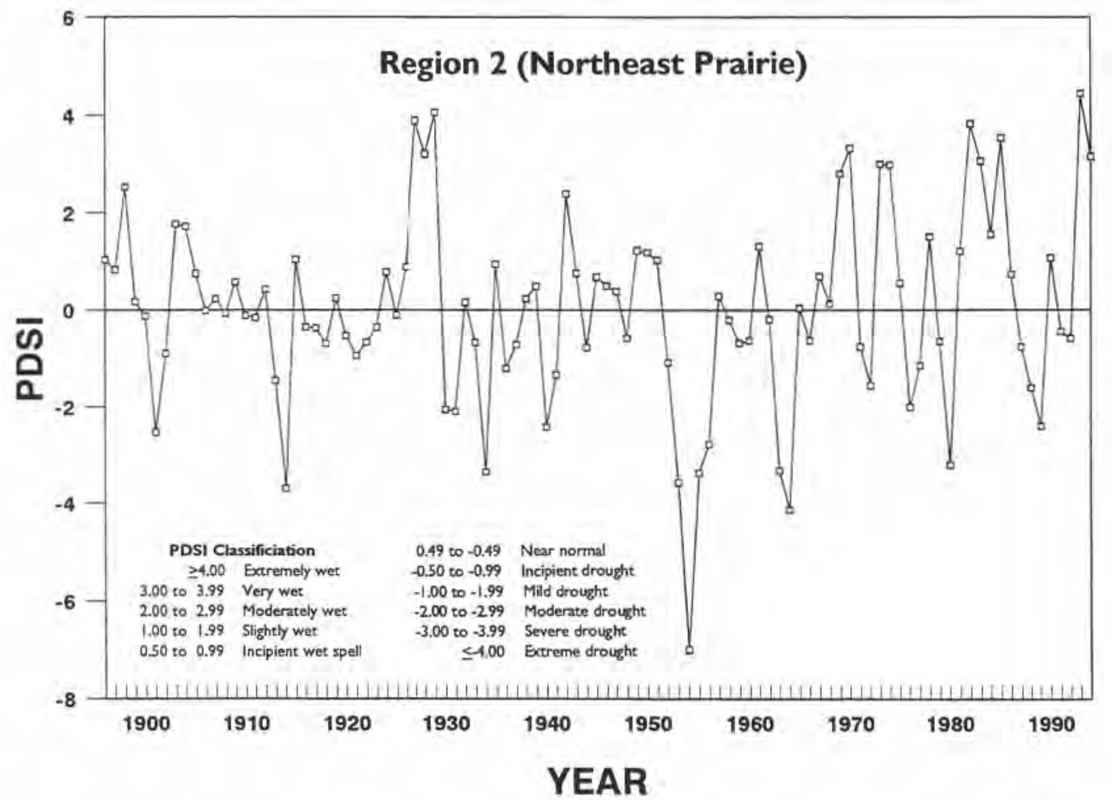


Figure 30. Average annual Palmer Drought Serverity Index - Northeast Prairie.

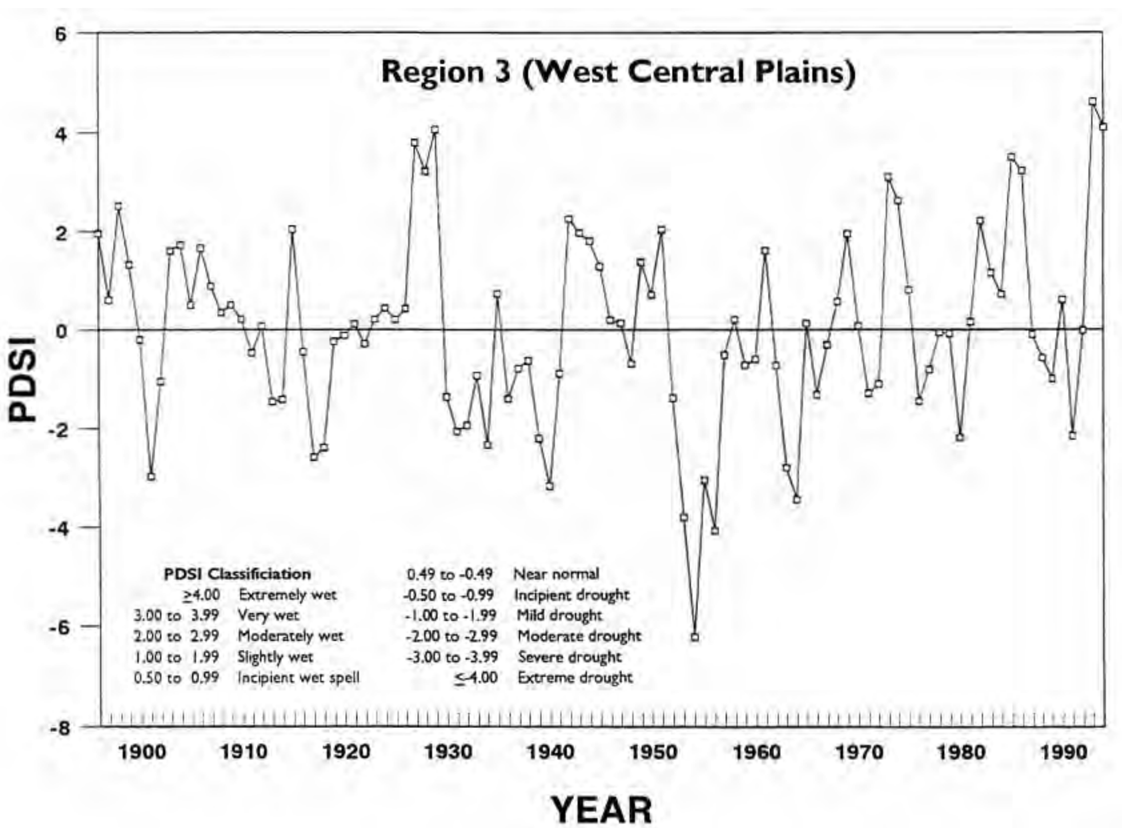


Figure 31. Average annual Palmer Drought Serverity Index - West Central Plains.

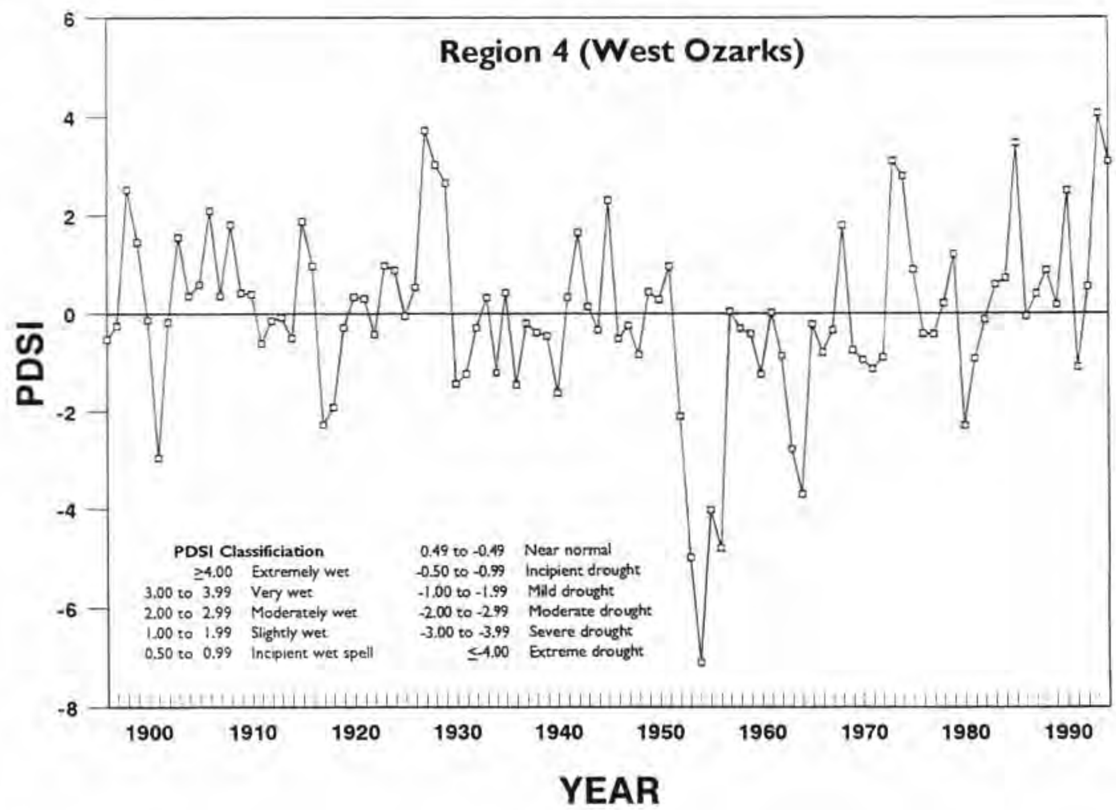


Figure 32. Average annual Palmer Drought Serverity Index - West Ozarks.

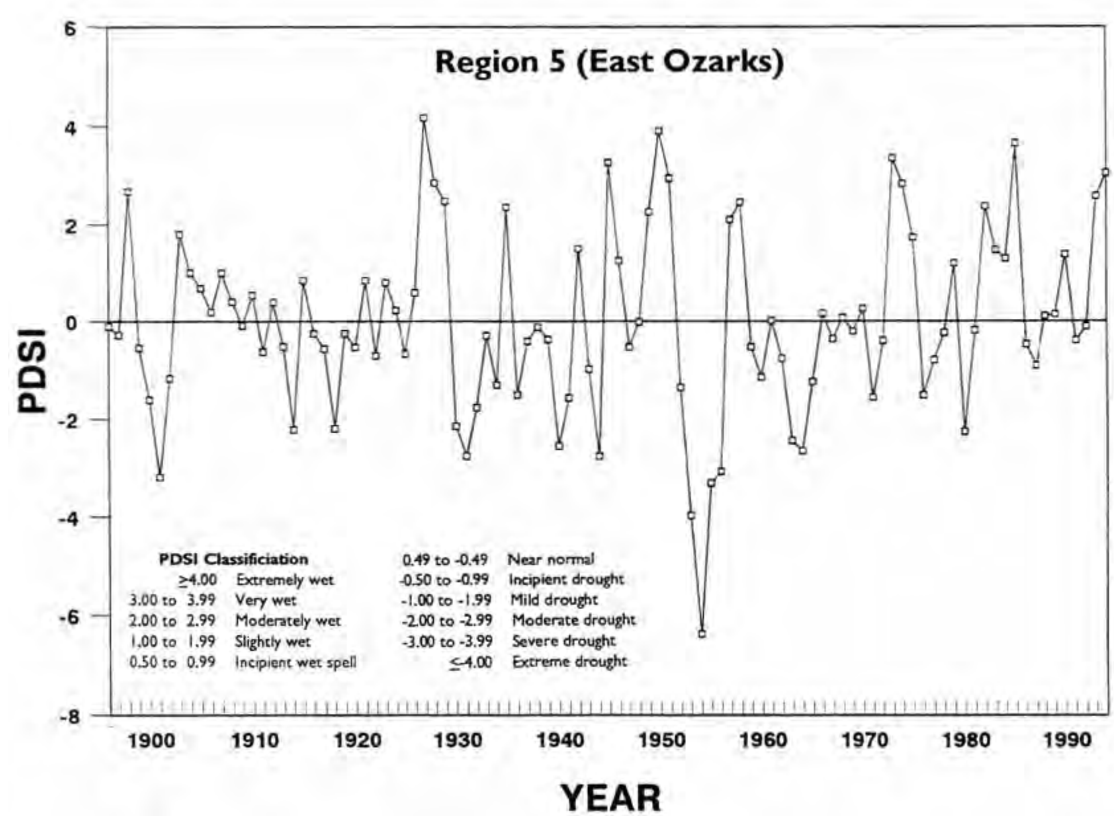


Figure 33. Average annual Palmer Drought Serverity Index - East Ozarks.

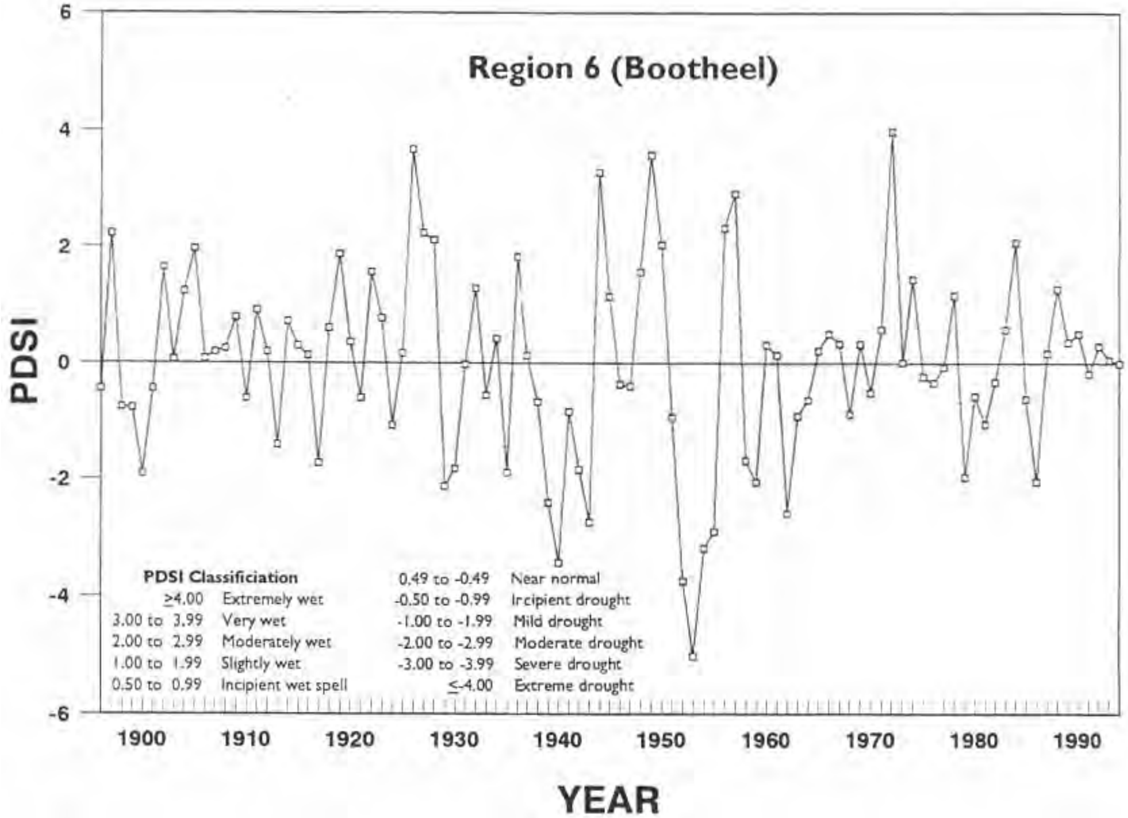


Figure 34. Average annual Palmer Drought Serverity Index - Bootheel.

Analytical Perspective - Tree Ring Studies

Another way to examine Missouri's climatic past is through the interpretation of tree rings. The physical basis in the study of tree rings is that a tree responds selectively to climatic and environmental conditions. Some of the conditions have a stronger influence on tree growth and ring width than others. The physiological responses of a tree act as a filter to climatic signals. Past climate can thus be "viewed" through the "window" (Guyette and McGinnes, 1980). However, site selection must be performed very carefully to get the desired climatic signals. This is because tree ring chronologies reflect complicated environmental conditions. To amplify the relationship between tree rings and precipitation, the best sites to sample trees are on relatively well-drained, dry sites, or where low soil moisture is likely to be the main environmental factor limiting growth (Fritts, 1976).

The study, *A Climate History of Boone County, Missouri, From Tree Ring Analysis of Eastern Red Cedar and White Oak* (Guyette et al., 1982), developed a tree ring index to correlate summer temperatures and spring rainfall. The index was also correlated with the Palmer Drought Severity Index (PDSI). Both oak and red cedar ring widths were correlated with growing season temperature and total precipitation. Both oak and red cedar ring width indices correlated well with drought-related variables such as the May-June mean maximum temperature, the Palmer Drought Index, streamflow and crop production. The ring widths of Ozark trees, particularly red cedar, are highly correlated with river discharge. Thus, there is potential for long-term reconstructions of hydrological conditions prior to the collection of streamflow records.

The indices from Boone County show agreement of narrow rings with other midwest chronologies in many key years. This study's interpretation of the ring width index provides insight into past climatic conditions:

1945-1955

The early fifties were very dry and hot in Boone County. This is one of the few places in the index with a downward trend in ring width for ten years.

1930, 34, 36

These were "signature" years, that is, years that show up narrow in almost every core and were very helpful in dating. When these years do not cross-date, it is a good indication the core cannot be used. These were the dry years of the dust bowl. Some trees showed injury in 1930—probably from fire or fence post cutting.

1917-1919

Two trees a half mile apart show wounding response in their bole. This could be due to logging or fire.

1898-1902

This was an extended period of low index values and distinctive because of its duration. There were record summer highs in Missouri and record low precipitation in Columbia, Missouri, in 1901.

1879, 81

There were signature years. They show up over much of southern Missouri, Illinois, and Arkansas as narrow rings indicating widespread drought. Cold winters also were reported for these years.

1860

This was an individual year of drought that shows well because of the wide rings before and after it.

1855, 56

These narrow rings also show up in a *Juniperus virginiana* (Eastern Red Cedar) chronology of Jefferson County, Missouri.

1836, 41, 43

Tree ring indices narrow in Boone, Jefferson and Shannon counties. These were dry years.

1784

Many samples from Boone County show a drop from their mean ring width this year. It would be 10 years before the index returned to the pre-1784 mean. This could indicate structural damage to the crowns of many trees. This may have been due to the severe winters of 1783-84, 1784-85, 1785-86 which occurred over much of the world. These severe winters were caused by a lack of radiation reaching the earth because of high quantities of dust that were thrown into the atmosphere by the eruption of the volcanoes Asama (Japan 1783), Skaptar, Jokul (Iceland 1783), and Vesuvius (Italy 1783). Benjamin Franklin writes, "the winter of 1783-84 was more severe than any that had happened for many years. (Sparks 1906).

1778-84

These were signature years. A very short 2-year cycle from 1778 to 1784 was preceded by a short period of extraordinarily good growth. This pattern appeared in Jefferson county and in the oaks *Quercus alba* (White Oak) in Southern Missouri. It was probably a period of alternating drought years.

1767-68

These were dry years in Jefferson and Boone counties.

1742

Wounding response can be seen in one tree, also a low point in index. Fire is a possibility.

1690-1720

This is a period of missing rings in several samples. If any period in the index had fire or drought, this period is the most likely. This was a period of extreme climatic variance in the Northern Hemisphere.

Guyette et al. also conducted tree ring research in the Ozark region. They examined the variation of drought in the region, using a record of climate, reconstructed from the annual growth increments of trees (Guyette et al., 1982). Two tree species were used for the

analyses, the eastern redcedar and white oak. The two species respond to climatic conditions differently. The conclusion of the research is that there are four patterns of drought frequency: (1) a biennial pulse or 2.3-year drought cycle, (2) some statistical evidence for a six-year drought cycle, (3) drought frequency in certain wavelengths of a time series (years) that can change for long periods (60 years), and (4) drought cycles that vary in strength through time.

Historical Perspective

A brief overview has been compiled from historical documents to provide a glimpse of drought in Missouri's past. The following are direct quotes from the sources listed.

1831

(Source: Shoemaker, 1934)

In 1831 there was a general drought in Missouri; creeks and rivers went dry, and many crops failed. It was necessary in the spring of 1832 to buy seed corn from Indiana and Kentucky which sold readily at the Hannibal steamboat landing and other places for $2 a bushel; in some regions it sold for as high as $4 a bushel.

(Source: Shoemaker, 1935)

The drought of 1831! The grass died, trees lost their leaves, wildlife migrated or was decimated, the crops failed, and seed corn from Kentucky for next year's planting sold at from $2 to $4 a bushel. Only fair crops were raised in 1832 and in some sections very little of the $4 seed repaid the farmer for its cost.

1891 to 1900

(Source: Shoemaker, 1943)

Poor weather conditions also plagued the farmers in the period between 1891 and 1900. August in 1892 was exceedingly dry, hampering the growth of the corn crop, and corn production was some 50,000,000 bushels under the crop of the previous season. This was partially due to a smaller acreage, however. Heavy shipments of horses from western ranges increased the number on hand and lowered the market price. The cattle market was dull, but hog prices remained relatively high. Crops were just fair in 1893, with the average yield of wheat dropping sharply. In 1894 drought struck again and before the end of the summer had become so severe that stock water was scarce. The drought was felt most severely over the northeast, northwest and central sections of the State. Crops were larger in 1895 but prices were still very low. There was a drought again in 1897, but prices had begun to rise by this time.

(Source: Meyer, 1982)

The droughts and the depressions of the last half of the nineteenth century produced great trials for farmers. During the mid-1890s, corn sold for as little as twenty cents a bushel, wheat forty-three cents a bushel, and oats eighteen cents a bushel. Many farmers who held mortgages signed when wheat brought $1.50 a bushel lost their land during the 1870s and the 1890s.

1901

(Source: Shoemaker, 1943)

A severe drought struck Missouri in the summer of 1901, and July 15 the Governor issued a proclamation setting aside Sunday, July 21, as a day of fasting and prayer, "that many threatened disasters from drought may be averted." The results of Governor Dockery's day of prayer did not prove as satisfactory as "Hardin's grasshopper prayers," for according to the official record the rainfall for both July and August continued to be considerably below normal. Wells and other water supplies were exhausted, cattle were shipped to other states for pasture, and thousands of acres of crops were injured.

(Source: Shoemaker, 1943)

In spite of the general prosperity of the period it got off to a bad start, for 1901 brought one of Missouri's worst droughts. The drought lasted for 100 days, from the middle of April to the last of July. Rainfall over the State for the period ranged from 7 to 70 percent of the normal rainfall, averaging only 38 percent of

normal for the entire State. All of the crops were disastrously hurt by the lack of rain, and the board of agriculture in August advised farmers to "sow rye for forage and hold their stock."

1930s

(Source: Meyer, 1982)

Severe drought further complicated the farm situation during the thirties. In 1930, 1934, and 1936 drought withered the crops, dried up ponds, creeks, and wells, and cracked the parched land like an old plate left too long in an oven. Unusually intense heat increased the misery of man and beast. In 1934 the residents of Columbia, Missouri, sweltered twenty-six days in temperatures over 100° and thirteen days in heat over 105°. Two years later another heat wave scorched Columbia with thirty-nine days over 100° and thirteen days over 105°. The summer of 1936 was made even more unpleasant by great swarms of grasshoppers which invaded the State. When the county agents of Missouri distributed a poison bran mash to curtail the grasshopper damage, those farmers who used the bait were able to save some of their crop. It was estimated that the grasshoppers that summer stripped the crops on approximately 1,000,000 acres of Missouri farm land.

(Source: Thomson, 1977)

Surveys made after the rains finally returned showed that in western Kansas between a third and a half of the native trees of all kinds were completely dead and many more had been badly injured. This included even the doughty bur oak. ... Losses were much higher among trees planted in windbreaks, hedgerows, and timber claims. The drought of the 1930's practically wiped out what little remained alive on the timber claims.

Throughout eastern North America the early thirties were unusually dry years, but the summer of 1934 brought the worst drought and heat that have ever been recorded on the prairie. That year the hot, dry, windy weather began in the spring, and by May the more shallow rooted plants had already begun to dry up as water disappeared from the upper part of the soil.

As the summer progressed, with nothing but light showers that scarcely laid the dust, the soil dried to deeper and deeper levels. Although in many summers the top six inches or so of prairie soil become completely dry, that year as early as July there was no water at all to a depth of three feet. In August the dry zone fell to four feet, and even at six feet there was very little moisture available for even the most efficiently absorbing roots.

The drought continued for seven long years. In that time occasional rains wet the top part of the soil, but this did not last long. Below the moistened layer the earth was a thick, dry zone between any surface moisture and the steadily falling level of deeply stored water. Through this barrier no roots could grow, and only those that had already grown below it could use the deep reserves.

In 1941 the rains at last returned to normal, and gradually moisture penetrated into soil that had long been totally dry. It was several years before the moist layer worked down far enough to meet the deep ground water. ... Although the remains of old grass clumps persisted and masses of roots were left underground, most of the plant matter was dead.

1930

(Source: Shoemaker, 1943)

Although for several years previous it had been prophesied that Missouri agriculture had reached its lowest level, by 1930 the State board of agriculture concluded that "Missouri agriculture has reached the bed-rock bottom." The year 1930 brought the most destructive drought since 1901. Farmers were urged to keep from selling their land since it was bringing far below its real value, but buying of land was encouraged. Many farmers who had gone heavily into debt, however, were faced with mortgage foreclosures and debts that could not be paid. The long-awaited increases in farm products prices, and the increase in demand and resultant rise in price of farm land, had not yet come.

1934

(Source: Shoemaker, 1943)

The year 1934 brought one of Missouri's most disastrous droughts. Farmers all over the State suffered severely. The Missouri Ruralist on August 1, 1934, reported that Missouri's corn crop "lost 100 million bushels in July, the oats crop is estimated at 10 percent normal, lowest in history and pastures at 15 and 20 percent normal, by official and semi-official reports. If rain holds off too long corn will be a failure. About 30 percent of the farmers are hauling water and emergency livestock marketing has started." The government aided by purchasing cattle farmers were unable to keep all winter and by the corn-hog and wheat programs which were already under way. The drought was compared to the droughts of 1901 and 1881, and farmers were urged to "Hold the line."

(Source: Thomson, 1977)

From mid-June to the end of July there was a heat wave to break the force of the cruel sun. The large areas of exposed soil provided a heyday for some of the aggressive native weeds such as peppergrass, horseweed, and pigweed; and much of what had been rich prairie came to look like an abused and weedy pasture. ... On the western plains, conditions are always drier, and except in special situations there is none of the deeply stored water that supports the lush vegetation of the tallgrass prairie. Here the common plants have long been adapted to hot, dry summers and to soil that is practically always dry below the level of a few feet.

(Source: Klinefelter, 1935)

The Mississippi River at St. Louis was at the lowest stage on record (years 1861 to 1934 inclusive) for January 1, which was 3.3 feet below zero.

Total precipitation for the state for the five months, October, 1933, to February, 1934, averaged 7.85 inches, whereas the normal average is 11.66 inches, therefore the rainfall for that period was only 67 percent of normal.

Rivers and small streams remained unusually low throughout the month; farmers were still hauling water and many of them were deepening their dry ponds and hoping for rain.

Outstanding features of the weather for April in Missouri were, (1) the very mild period of the 1st-5th and 8th-10th; (2) the very cool periods of the 12th-14th, 20th-21st, and 24th-28th; (3) the marked deficiency in rainfall in all parts of the State; and, (4) the absence of damaging frost. The month was unusually free from damaging windstorms, but several dust storms occurred, the one on April 11 being reported by observers at Springfield as "probably the worst ever experienced here."

The month of May, 1934, was decidedly drier and warmer than normal. The average rainfall for the State was only 40 percent of the normal, the driest May since 1914. The extensive drought of April, of which Missouri was only a small part, developed in intensity, and by the end of May the drought was the most severe in the climatological history of Missouri, for so early in the year. Dust storms, probably the most severe on record, occurred on the 9th, 10th, and 11th. At times the sun was almost totally obscured and visibility frequently was less than one-half mile. The dust interfered considerably with breathing. All exposed places were rapidly covered, and even considerable deposits of dust were noted on the interior of residences and office buildings in the cities. While fairly good rains occurred on the 13th and 14th, they only gave temporary relief. By the end of the month much of the late planted corn had not germinated, oats and hay had made very little growth, and wheat was deteriorating rapidly. The stream flow of the large rivers was much retarded, resulting in the lowest May stages ever recorded for the Missouri and Mississippi Rivers at St. Louis.

There was considerable range in temperature during May-from 31 degrees at Elsberry on the 25th, to 110 degrees at Maryville on the 30th. Damaging frosts occurred on lowlands in St. Louis, Franklin, and St. Charles Counties on the night of May 24-25th, causing serious dam-

age to garden truck. Some plantings were entirely killed, while others nearby were not affected. Light frosts also occurred in Scotland and Audrain Counties, but no damage was reported. The unseasonably low temperatures of the 25th and 26th were followed by unusually high temperatures on the 30th. Such high temperatures have never been recorded so early in the season. The 110 degrees at Maryville is the highest May temperature of record (1888-1934) for the State. The average precipitation for the State was 2.84 inches less than normal.

It was the warmest June, for the State as a whole, since State-wide records began in 1888. The average temperature, 80.4 degrees, was 1.1 degrees higher than the previous highest average for June, which occurred in 1914. While it averaged warmer than any other June of record, the absolute maximum temperature for the month, 108 degrees, has been slightly exceeded by the month of June in past years, notably, in 1911, when 112 degrees was registered. The heat was persistent throughout the month. Rainfall was light, the State average being 2.85 inches for the month, but June has had less rainfall eight times in the last 46 years. However, the rainfall was very deficient during the whole six months period, January to June, inclusive, and the cumulative effect was severe drought in most parts of the State during June. The southeastern quarter suffered less than other sections. The first six months of 1934 had less precipitation than any other corresponding six months of record (1888 to 1934); the total this year was 12.02 inches, while the least heretofore recorded was 13.12 inches, in 1901. Hail on various dates caused considerable damage.

Following a June that was the warmest of record, July had not only record-breaking high temperatures on individual dates, but the general average for the month was higher than ever before in the history of Statewide records. For many years the hot July of 1901 had held the record, but 1934 now holds first place; for the highest temperature heretofore recorded was 116 degrees on July 22, 1901, at Marble Hill, whereas, the 1934 July shows a record of 117 degrees at Louisiana, Pike County, on the 18th. Mexico, in the same quarter of the State, had 116 degrees on the 24th. The highest in the Northwestern quarter was 114 degrees at Marble Hill. Furthermore, the general average for the State, 86.2 degrees, was 0.8 degrees higher than the previous highest average, July 1901. There were only a few days with temperatures anywhere near as low as normal, but the outstanding hot period extended from the 11th to the 25th, inclusive, during which the maximum temperature every day was well above 100 degrees at most weather stations. The average rainfall for the State, 1.11 inches, was the second smallest July of record, the total for July 1930 having been 0.97 inch. The rainfall was unevenly distributed over the State, with as much as 5.22 inches at the wettest station, Clinton, and none at the driest, Palmyra. The State rainfall for the four months, April, May, June, and July, was 8.26 inches, or 48 percent of normal, and is the least of record, being slightly less than for the same months in 1901, when it was 8.47 inches. For the seven months, January-July, the total for 1934 was 13.13 inches, decidedly the least of record, being 2.01 inches less than for the same months in 1901.

The extreme heat and drought of July continued into August, and the spell was not finally broken until about the 16th, although beginning to weaken about the 11th. Long standing records of August high temperatures were broken during the first 10 days this month. But the second half of the month was in marked contrast, being decidedly cooler than normal and with minimum readings on the 29th at some stations lower than ever before recorded in August. Rains were too late to be of much benefit to corn. They helped forage crops, gardens, and pastures, and enabled farmers to sow wheat, rye, and barley, for pasture, and they brought relief in furnishing water for domestic use.

The period of rains and cool weather that began about the middle of August, putting an end to the record-breaking spell of heat and drought, continued through September. September was a cool, wet month. The average temperature for the State, 65.6 degrees, is the lowest September average since 1928. The

average rainfall, 7.39 inches, is the third greatest September average of record for Missouri.

The 1934 drought has had a profound effect upon agriculture. Of a general nature, covering all sections of the United States except a few southeastern states, it wiped out the surplus of livestock numbers-Cattle in particular, which had been on the increase for six years. Enormous surpluses of corn, wheat and other cereals were also wiped out with the result that importations of grains and hay were necessary. For the first time in history, a cargo of wheat was imported from France. One of the crops that best survived the drought in Missouri was alfalfa, while winter barley was sown extensively for the first time in the State to supplement the acute feed shortage. A total of 509,440 head of cattle and 7,547 sheep were bought by the government in Missouri some of which were processed immediately, with others of the thinner sort shipped to southeastern states where pastures were good and later to be slaughtered and fed to the 20 millions of people on relief rolls. Old and weak animals unable to survive shipment were killed at the farm and buried. Seed of all kinds, except wheat, has become exceedingly scarce owing to drought, and higher prices are resulting. Many excellent herds of breeding stock had to be sacrificed because of the feed shortage. The price of hay has been restored practically to war-time figures. All in all, 1934 was a year that will be long remembered, by farmers in particular. Perhaps the only solace to be gained from a review of its unusual weather is the thought that future years are apt to be better ones.

1936

(Source: Shoemaker, 1943)

In 1936 drought struck again, and the report of the department of agriculture labeled it worse in some counties than the 1934 season. In addition the plague of grasshoppers visited Missouri, laying waste many acres of land in some thirty counties. Much of the destruction was in the important corn counties, and the corn crop as a result was of poor quality. The fruit crop was also the smallest in many years. The total value of farm crops showed a decrease of 2.7 percent as compared with 1935.

1954

(Source: St. Louis Globe-Democrat, 1954)

Many communities in Missouri and Kansas, the states whacked only three years ago by devastating floods, are faced with a very different crisis today; they're drying up.

A merciless drought that lasted through the summer still shows no sign of abating. It's no longer just the preoccupation of worried farmers, but has moved, quietly, into the cities and towns.

A sign of the times are big, 1000 gallon water trucks hauling supplies to farm lands and thirsty cities throughout northern and central Missouri and eastern Kansas.

Some 20 hauling companies are engaged in the water trade in Jefferson City, Missouri, alone. The state capital lies on the Missouri River, so its own supply is ample, and water is being shipped out in a 60-mile radius.

Springfield, Missouri, has taken to cloud-seeding to produce rain, without results to date.

At Edina, Missouri, the army recently had to step in and build an emergency pipeline to a nearby lake to replenish the community's reservoir-which since than has run perilously low once more.

Lamar, Missouri, is precariously getting by on a well formerly supplying an ice plant. Residents of Princeton, Missouri, were dismayed last week to find that one of their two supply wells had gone dry.

(Source: Missouri Farm Bureau News, 1954)

Farm losses from the drought in Missouri were estimated recently at $200,000,000. The cost of restoring the state's pastures aline has been put at a minimum of $100,000,000. This staggering total does not include business losses from the drought in the last year. To it must be added the millions of dollars in flood damages in previous years which might also have been substantially reduced had Missouri had a sound water conservation and use policy.

Many Missouri communities are faced with a critical shortage of water for municipal

use. In Jefferson city, for example, more than 2,000,000 gallons of water were pumped out of the Missouri River in January for distribution by haulers over Cole County. In some parts of the state, towns are being forced to limit the use of water by farmers in order to conserve their dwindling reserves. Bowling Green for the last month has been forced to haul all of its water from Louisiana, 12 miles away.

Last summer low water stages in many streams created a serious health hazard when there was not enough water to carry away the sewage. Had it not been for water released from the upstream reservoirs in the Missouri Basin, sewage disposal would have been a critical problem last summer in Kansas City and even at St. Louis.

One phase of the problem which has received little attention is the falling underground water levels in this state. The falling water tables not only affect agriculture, but create new problems to communities which receive their water supply from wells.

(Source: St. Louis Globe-Democrat, July, 1954)

Fifty-six Missouri Counties have critical water shortages and 22 others may become critical in the next two weeks, Dr. Edward L. Clark, state geologist, reported to Gov. Donnelly today.

(Source: St. Louis Globe-Democrat, September, 1954)

Missouri's three-year drought threatens to reduce Big Spring, said to be the largest in the nation, to its lowest flow in history. Three rivers which serve as important water sources as well as tourist attractions in southwest Missouri already have hit the lowest stages on record.

(Source: Jefferson City Post-tribune, 1954)

President Eisenhower assured Gov. Phil M. Donnelly today Missouri's request for immediate federal drought aid would get prompt attention. At the same time the state launched a new attack on the critical underground water problem.

The president said he had read the governor's appeal that the entire stage be designated a drought disaster area with sympathetic understanding.

1988

(Source: Changon, 1989)

One of the worst droughts of the 20th Century peaked in the contiguous United States during 1988. Its impacts were pervasive, affecting agriculture, water resources, transportation, recreation, and wildlife. Costs and losses amount to nearly $40 billion, making it the worst natural hazard of this century.

The President's Interagency Drought Policy Committee (1988) estimated that the total drought losses in agriculture alone during the last three-quarters of 1988 were $13 billion of direct GNP. This increased retail food prices in the U.S. by half a percent. In combination with impacts on energy, water, ecosystems, and other aspects of the economy, the drought cost the U.S. roughly $40 billion, making it the most costly natural disaster ever to affect the nation.

Because of the great extent and intensity of the drought, all aspects of our environment and society were affected. The

greatest economic loss was in agriculture, where more than $15 billion in crop losses occurred. There were 20 to 50% reductions in corn, soybean, and spring wheat production.

The summer 1988 heat wave was extensive with summer temperatures rated as the highest on record over 13% of the nation, including the major metropolitan areas of the Midwest and Northeast. The result was an estimated 5,000 to 10,000 deaths related to heat stress (Avery, 1988).

The environment was notably affected with major reductions in water supplies and diminished water quality in streams and wetlands. Forest fire damage in the West was the greatest on record, and the populations of certain species of wildlife in the Mississippi River Basin were reduced from 5 to 30%. The environmental effects will be the most long-lasting of all the effects of the drought of 1988.

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APPENDICIES

APPENDIX 1

MODELS/EQUATIONS

The following discussion provides a brief overview of some of the computer models and other techniques available for analyzing hydrological extremes. The discussion is not intended as an endorsement of any programs.

HEC-1

HEC-1, Flood Hydrograph Package, is a computer program developed by the Hydrologic Engineering Center (HEC), U.S. Army Corps of Engineers. The HEC-1 model is designed to simulate the surface runoff response of a river basin to precipitation. The discharge hydrographs can be either historical or hypothetical events. The basin is represented as an interconnected system of hydrologic and hydraulic components. Each component models an aspect of the precipitation-runoff process within a portion of the basin, commonly referred to as a sub-basin. The result of the modeling process is the computation of streamflow hydrographs at desired locations in the river basin.

HEC-1 includes four major components for modeling catchment response to precipitation: (a) rainfall-runoff computation; (b) routing; (c) hydrograph combining; and (d) flow diversion. An economic analysis component is available for flood damage computation. HEC-1 allows a wide variety of options for specifying precipitation, losses, base flow, runoff transformation, and routing.

The available program options include the following: calibration of unit hydrograph and loss-rate parameters, calibration of routing parameters, generation of hypothetical storm data, simulation of snowpack processes and snow-melt runoff, dam safety applications, multi-plan/multi-flood analysis, flood damage analysis, and optimization of flood-control system components.

A detailed description of the concepts, methodologies, input requirements and output formats used in HEC-1 model can be found from the user's manual. The model can be obtained from the vendors of the U.S. Army Corps of Engineers, Water Resources Support Center, Hydrologic Engineering Center. The vendors supply the compiled program or source code and also provide various degrees of program support. HEC-1 is available directly from the Hydrologic Engineering Center only to U.S. government agencies. A list of program vendors is available from the Hydrologic Engineering Center, 609 Second St., Davis, CA 95616.

TR-20

Technical Release 20 (TR-20) is a single-even rainfall-runoff model developed by the U.S. Soil Conservation Service. TR-20 calculates runoff hydrographs, routes flows through channel reaches and reservoirs, and combines hydrographs at confluences of the watershed stream system.

The model is normally used with a design storm as rainfall input. Runoff hydrographs are computed by using the SCS runoff equation and the SCS dimensionless unit hydrograph. Computed flows are routed through channel reaches and reservoirs.

The watershed is divided into sub-basins with similar hydrologic characteristics, which are based on the location of control points through the watershed. Control points are placed at tributary confluences, a structure, a reservoir, a diversion point, a damage center, or a stream gauge.

TR-20 uses land-use information and soil maps, indicating soil type, to define the SCS curve number for specific land areas. The SCS dimensionless unit hydrograph is defined by watershed lag and the sub-basin area. Standard procedures are available for determining the lag.

The TR-20 model has been widely used by SCS engineers in the United States for urban and rural watershed planning, for flood insurance and flood hazard studies, and for local agencies also.

The TR-20 program is available in different formats. There are versions of TR-20 for the PC. Other versions exist for mainframe and microcomputers.

The microcomputer(PC) version of the program is available from local SCS offices. The various versions of the program for other types of computers can be obtained from the Soil Conservation Service, U.S. Department of Agriculture, Washington, D.C. The TR-20 report can be obtained as PB-8818-4122 from National Technical Information Service, 5285 Port Royal Rd., Springfield, VA 22161.

TECHNICAL RELEASE TR-55

Technical Release 55 (TR-55), "Urban Hydrology for Small Watersheds" is a simplified version of TR-20 that does rainfall-runoff modeling for a single watershed. It was released by USDA Natural Resources Conservation Service (NRCS) in 1986. TR-55 was prepared to calculate storm runoff volume, peak rate of discharge, hydrographs and storage volumes required for detention structures. The procedures are simplified and applicable in small watersheds, especially urbanizing watersheds, in the United States.

The model starts with a rainfall amount uniformly imposed on the watershed over a specified time distribution. Mass rainfall is converted to mass runoff by using a runoff curve number (CN). Runoff is then transformed into a hydrograph by using unit hydrograph theory and routing procedures. Although the TR-55 gives special emphasis to urban and urbanizing watersheds, the procedures apply to any small watershed in which certain limitations are met.

Copies of the Technical Release 55 (TR-55) are available from the National Technical Information Service (NTIS), Springfield, Virginia.

REGIONALIZED EQUATIONS

There are many ungaged watersheds in the state. This is especially true on smaller watersheds. The U.S. Geological Survey developed a set of equations that estimate peak discharge for small basins in Missouri. The equations were developed for the 2, 5, 10, 25, 50 and 100 year recurrence interval.

In cooperation with the Missouri Highway and Transportation Commission, the USGS also developed regionalized equations that estimate lag time and runoff volume. These equations can be applied to watersheds ranging from about 0.25 square miles to 40 square miles.

The equations present a relatively quick and easy method to estimate the magnitude, timing and volume of runoff which can be expected to occur at some given frequency. Where gage data is absent, the equations provide a very good tool for design and planning.

A detailed discussion of the equations can be found in Becker, L.D., 1986, *Techniques for estimating flood-peak discharges from urban basins in Missouri:* U.S. Geological Survey Water-Resources Investigations 86-4322, 38p. and Becker, L.D., 1990, *Simulation of Flood Hydrographs For Small Basins in Missouri:* U.S. Geological Survey Water-Resources Investigations 90-4045, 40p.

More recently the USGS in cooperation with the Missouri Highway and Transportation Department developed another set of regionalized equations for unregulated streams in the state. Using drainage area and channel slope you can estimate peak discharge for recurrence

intervals ranging from 2-year to 500-year. These equations are can be applied to gaged or ungaged streams. The equations were developed using data from watersheds which ranged from 0.13 square miles up to 14,000 miles. A detailed discussion of the equations can be found in Alexander, T.W., and Wilson, G.L., 1995, *Technique for Estimating the 2- to 500- Year Flood Discharges on Unregulated Streams in Rural Missouri:* U.S. Geological Survey Water Resources Investigations Report 95-4231, 33p.

SWRRB

Simulator for Water Resources in Rural Basins (SWRRB) was developed by the U.S. Department of Agriculture to simulate hydrologic and related processes in rural (agricultural) basins. The computer program was designed to predict the effect of various types of watershed management procedures on water and sediment yields in ungaged rural basins. The major processes performed by the model are surface runoff, evapotranspiration, transmission losses, pond and reservoir evaporation, sedimentation, and crop growth. SWRRB is also capable of simulating the runoff of pesticides.

SWRRB can deal with large basins which are subdivided into as many as 10 sub-basins, each of which can have a different rainfall input. There is no limitation on basin area. The soil profile can be divided into as many as 10 layers.

There are three major components in the model: hydrology, weather, and sediment yield.

The SWRRB hydrology model is based on the water balance equation. The change in soil water content is computed from rainfall, runoff evapotranspiration, percolation, and return flow. Basins are subdivided to reflect differences in hydrologic characteristics, such as the different evapotranspiration rate for different crops, soils, and other factors. The runoff from each is computed separately.

The major weather components used in this model are precipitation, air temperatures, and solar radiation. Precipitation can be used as a direct input, or be simulated as a first-order Markov chain process. Air temperatures and solar radiation for each day are generated from daily statistics of these variables.

The computation of sediment yield for each sub-basin is based on the modified universal soil loss equation in the model. Sediment yield is computed from the surface runoff volume, the peak discharge, a soil erodibility factor, a crop management factor, an erosion control management factor, and a slope-length-steepness factor.

SWRRB provides access to meteorological statistics compiled for about a hundred first-order-weather stations (with observations of precipitation, temperature, evaporation, radiation and wind speed) in the United States. SWRRB also contains a very extensive database of soil properties developed by the U.S. Department of Agriculture.

The SWRRB is available from the Grassland, Soil, and Water Research Laboratory, Agricultural Research Service, U.S. Department of Agriculture, 808 east Blackland Rd., Temple, TX 76502.

HEC-2

The HEC-2 is a computer program, released by the Hydrologic Engineering Center (HEC). The program has been developed to calculate water surface profiles for steady gradually varied flow in natural or man-made channels. Profiles can be computed for either subcritical or supercritical flows.

HEC-2 has been designed to consider the effects of various obstructions such as bridges, culverts, weirs, and structures in the flood plain in the computations. The program is also designed for application in flood plain management and flood insurance studies to evaluate floodway encroachments. Also, capabilities are available for assessing the effects of channel improvements and levees on water surface profiles.

Computations are based on the solution of the one-dimensional energy equation with energy loss due to friction evaluated with Manning's equation. Contraction and expansion losses can also be considered. The profile computation procedure employs the Standard

Step Method. Standard Step Method applies Bernoulli's theorem for total energy at each cross section and Manning's equation for friction loss between cross sections.

HEC-2 allows the user to select from four equations to estimate the energy loss term in the energy balance. Users can also specify coefficients for contraction and expansion.

The program requires identification data as the input. Individual data records have a two-character identifier at the beginning of each record. Multiple title records can be used, and comments can be inserted at any point in the data file. In addition, the program requires job control information, discharge and loss data, and cross-section geometry data. The cross-section data make up portion of the input and include cross-section numbering, reach lengths, geometry data, and modifications to the basic cross-section data (points added to cross section, filling of all low areas to a specified elevation, blocking out of ineffective flow areas).

HEC-2 is available directly from HEC only to U.S. government agencies. HEC provides lists of program vendors for the United States and other countries (Hydrologic Engineering Center, 609 Second St., Davis, CA, 95616).

The Hydrologic Engineering Center is developing a new software named HEC-RAS (River Analysis System) which may replace HEC - 2 sometime in the future. Version 1.0 has capabilities much like HEC - 2, with improved bridge hydraulics and a graphical user interface designed to make it easier to use the software. Two components that are planned for the model but were not available in Version 1.0 are unsteady flow simulation and sediment transport/movable boundary computations.

WSPRO

The WSPRO model calculates steady-state water surface profiles in open channels. It was designed for use with natural channels such as rivers and streams, where the geometry of the cross section changes from section to section. The computer program provides capabilities for analyzing flow through bridges and culverts, through multiple-opening stream crossings, and embankment overflows.

This model employs conventional step-backwater analyses. It assumes that the flow is one-dimensional, gradually varied steady flow. The water surface profiles can be computed for either subcritical or supercritical streams.

The WSPRO program can perform 1-20 individual water surface elevation profiles in a given run. Usually a different discharge is used for each profile. The discharge can be changed at each cross section. The water surface elevation at the starting cross section can either be specified by the user or be computed by the program.

WSPRO allows simultaneous variation of bed roughness both across the cross section and with water depth. Friction-loss computations are based on specified flow lengths between cross sections. The users can select the technique used by the program for computing the average friction slope. Coefficients for energy losses associated with expansion and contraction of the flow may be specified as input.

The WSPRO program was initially developed to provide bridge designers with a tool for analyzing alternative bridge openings and embankment configurations. Because of its usefulness for general stream profile computations, it is widely used in highway design, flood plain mapping, flood insurance studies, and developing stage-discharge relationships.

The WSPRO program can be obtained from the U.S. Geological Survey, WRD, 415 National Center , Reston, VA 22092, or from the Federal Highway Administration, U.S. Deportment of Transportation, Washington, D.C. A number of vendors of hydrologic models will also supply the program, either in complied form for use on personal computers or in ASCII format for other types of computer systems.

APPENDIX 2

WATER BALANCE PARAMETERS

PRECIPITATION

A major source of precipitation data for Missouri is the National Weather Service (U.S. Department of Commerce, National Oceanic and Atmospheric Administration). Figure 1 through 6 show stations that have precipitation data for Missouri. As can be seen in these figures, precipitation stations are distributed evenly around the state. Precipitation data is generally of good quality.

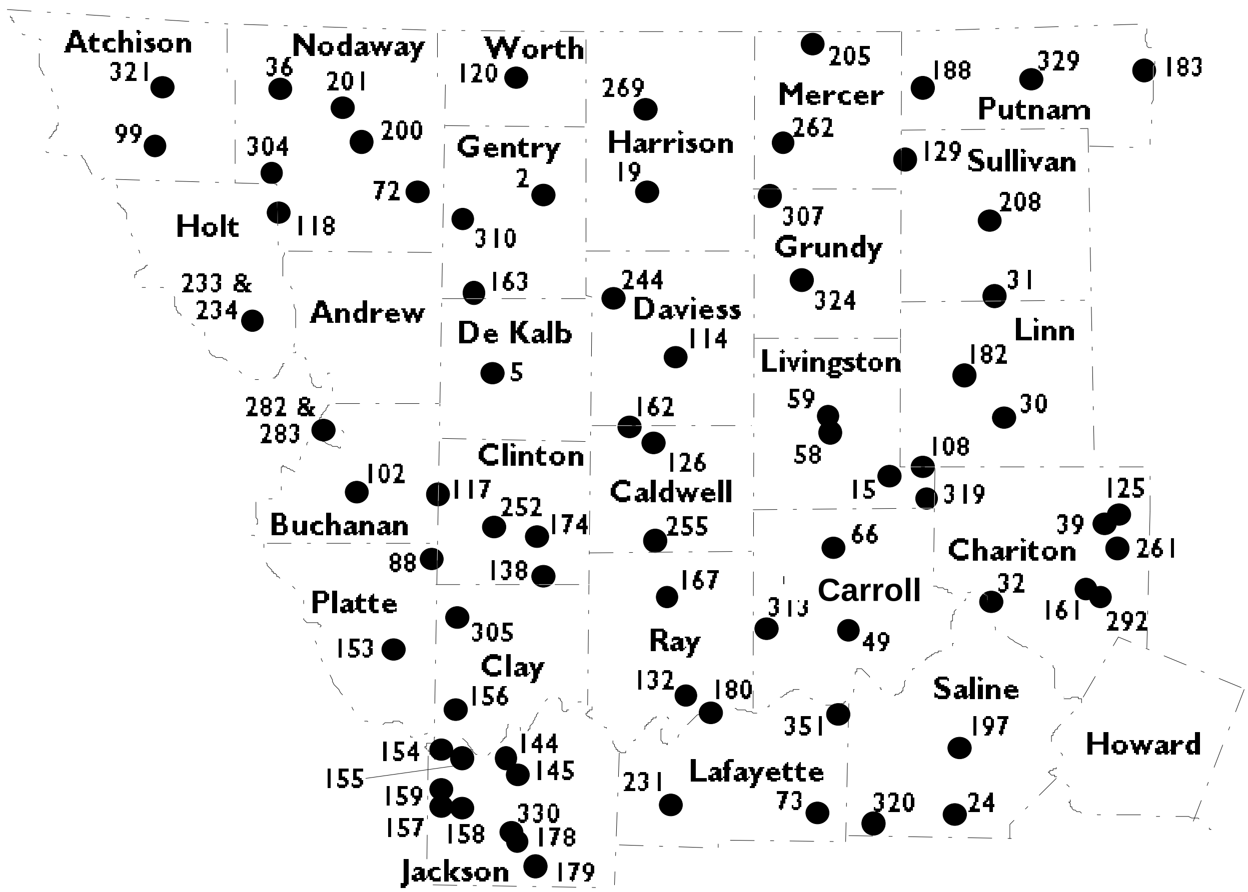
Precipitation amounts vary greatly across the state and from year to year. Annual precipitation recorded at Conception in north Missouri, has ranged from a minimum of 15.53 inches in 1988 to a maximum of 62.44 inches in 1993. Kennet in southern Missouri has recorded an annual minimum precipitation of 25.37 inches in 1963 and a maximum of 86.75 inches in 1957. Table 1 lists other maximum, minimum and mean precipitation totals for several locations in Missouri.

EVAPORATION

Evaporation is an important component of the water balance equation. Evaporation includes water lost from lakes, ponds, rivers and topsoil. Evaporation data for Missouri is available in the Climatological Data published by the National Climate Data Center (NCDC). In contrast to precipitation stations, there are not very many evaporation observation stations in Missouri. The length of record is also somewhat limited. Of the fourteen evaporation stations that were established, only six are still operating within the state. The spatial distribution of the fourteen stations are shown in Figure 7. Table 2 lists each station's name, ID, beginning year, ending year, total years and percent coverage. Of the six existing stations: two are in region 1 (6012, 7862), one is in region 2 (7452), one is in region 3 (6777), one is in region 4 (5862) and one is in region 6 (6804). The NCDC evaporation station in region 5 has not been operating since 1948. Among the fourteen evaporation stations, six have more than twenty years of records, and three stations have more than thirty years of records. The percent coverage for these stations is low (40-50%). Only Lakeside has coverage over 60 percent (69%).

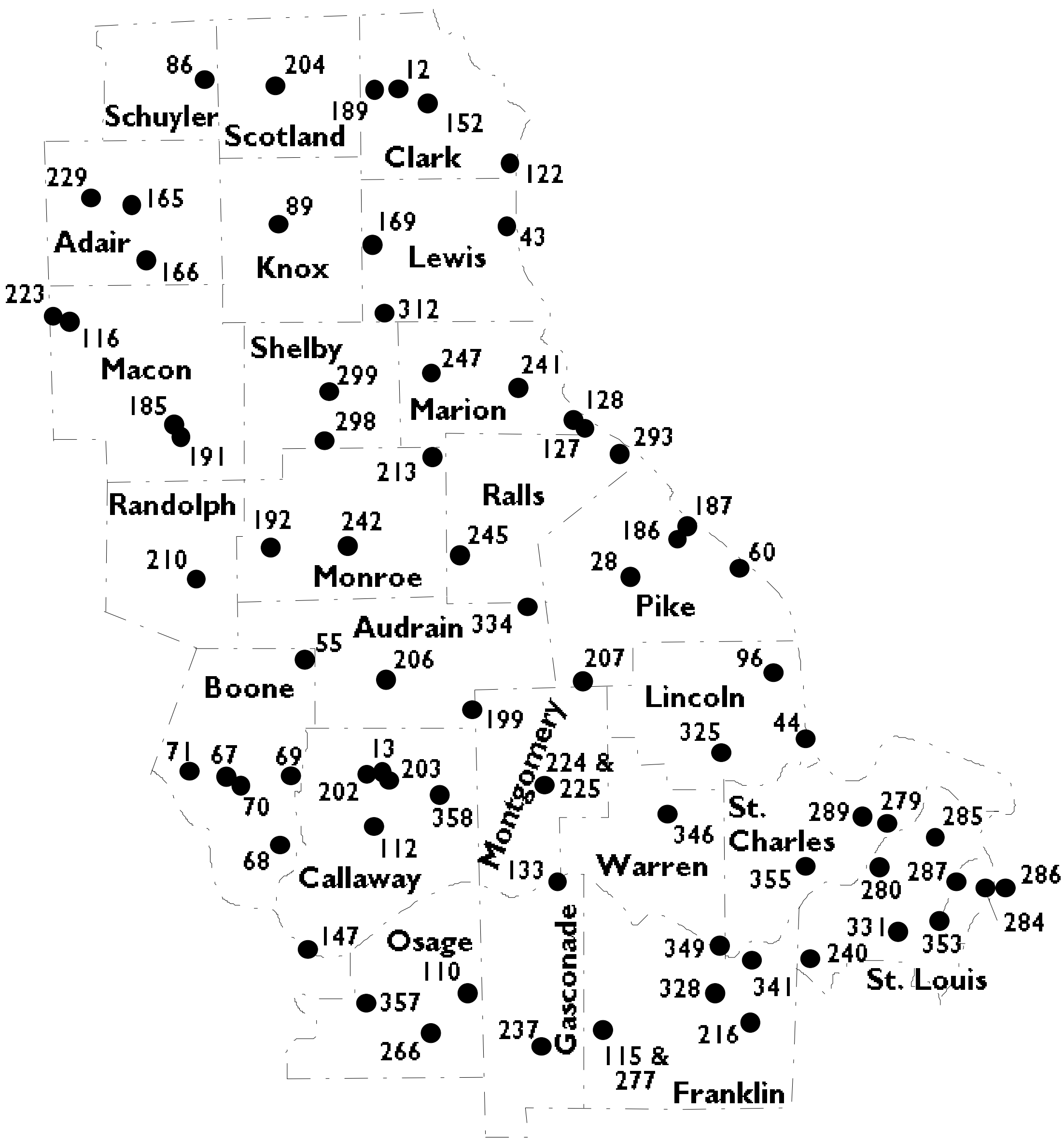
Evaporation stations collect pan evaporation data. Pan evaporation is typically measured using a shallow round metal pan, partially filled with water. Pan evaporation can be converted to free water surface evaporation using pan coefficients. Free water surface evaporation is a theoretical term used to describe evaporation from a thin layer of water having no appreciable heat storage. It is useful in representing evaporation from the surface of plants or soils (Farmsworth, 1982,). It is also used to approximate the evaporation from lakes and ponds. Since free water surface evaporation assumes no changes in heat storage, this is somewhat inaccurate. Actual evaporation may be less in the spring when a water body is heating up, and larger in the fall when heat is being released by a water body.

Figure 8, 9 and 10 depict the average annual free water surface evaporation, May through October pan evaporation, and the pan



Source: National Climatic Data Center

Figure 1. Precipitation station locations, Region 1 (Northwest Prairie).



Source: National Climatic Data Center

Figure 2. Precipitation station locations. Region 2 (Northeast Prairie).

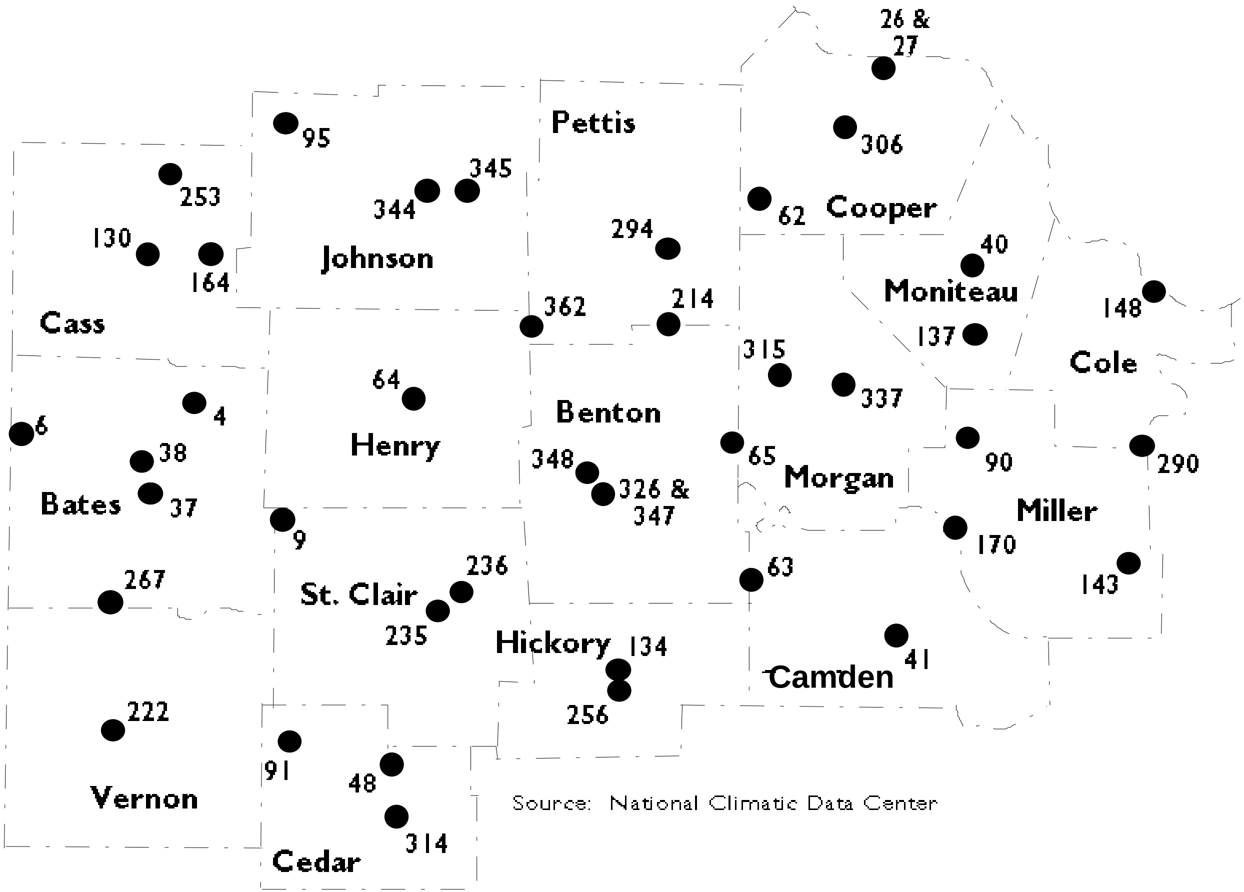


Figure 3. Precipitation station locations, Region 3 (West Central Plains).

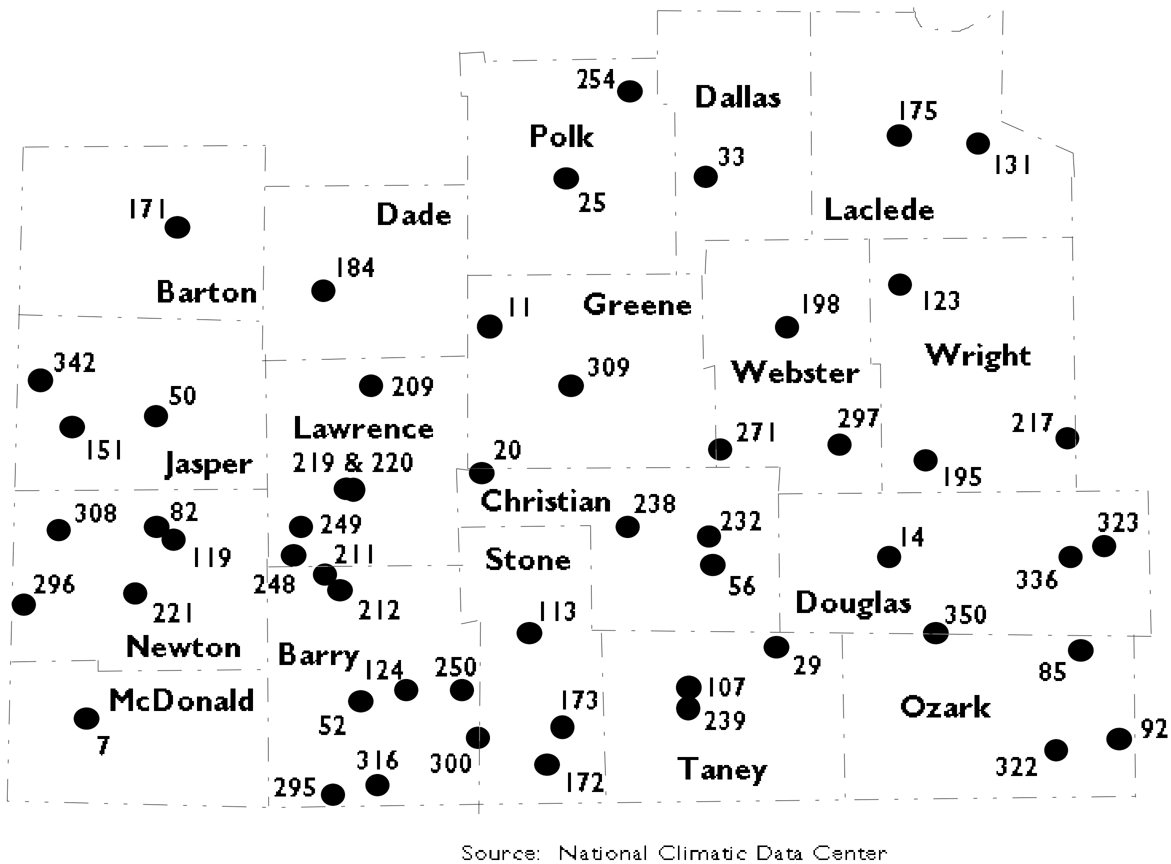


Figure 4. Precipitation station locations, Region 4 (West Ozarks).

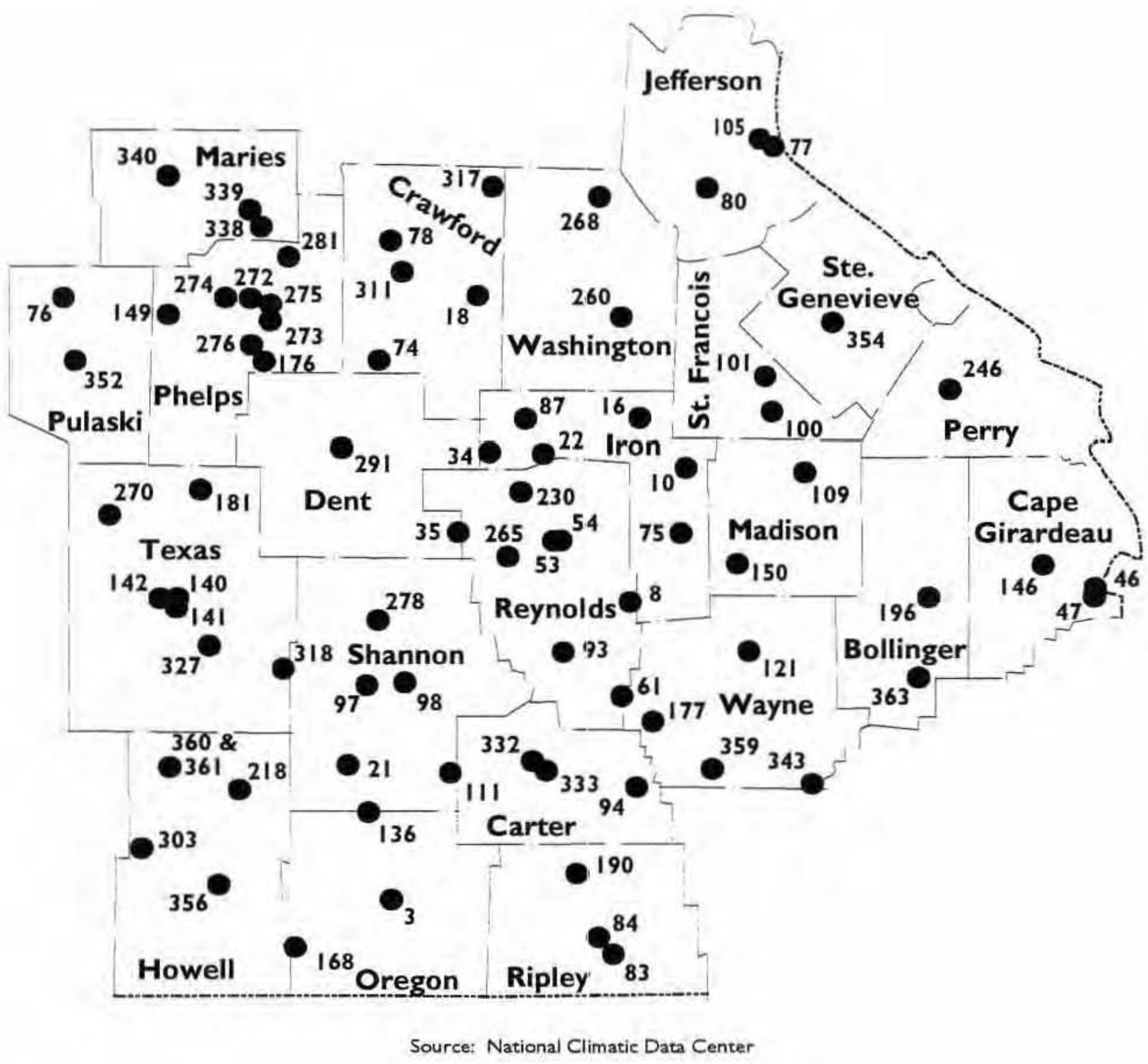


Figure 5. Precipitation station locations, Region 5 (East Ozarks).

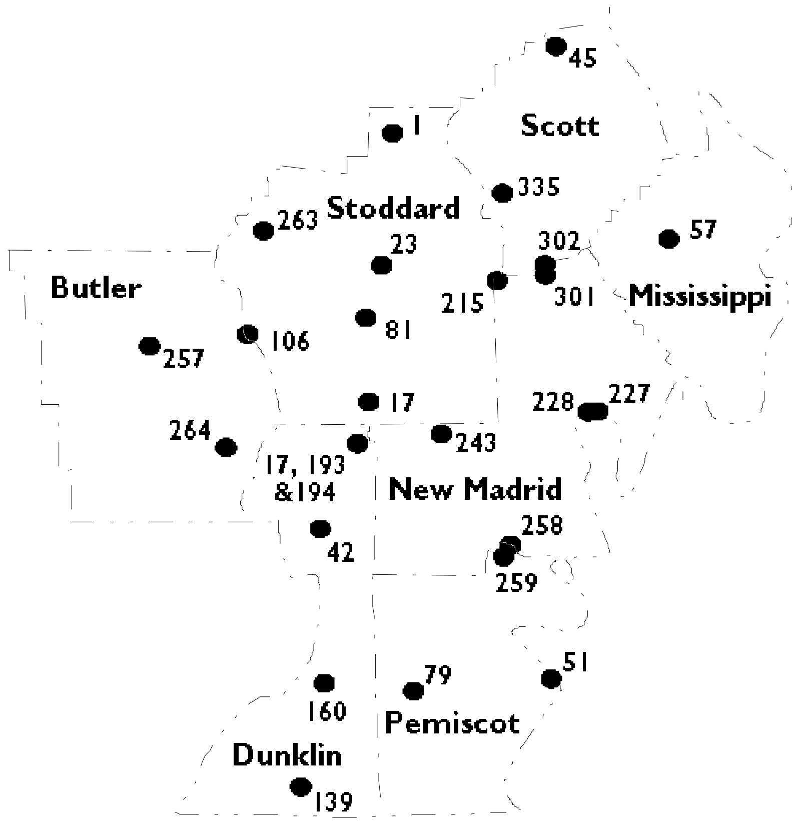


Figure 6. Precipitation station locations, Region 6 (Bootheel).

Table 1. Precipitation station annual statistics. (Source: National Climatic Data Center)

STATION NAME	Index	Years of record	Maximum (inches)	Year	Minimum (inches)	Year	Mean (inches)
ADVANCE 1 S	1	46	67.10	1957	31.00	1980	45.87
ALBANY	2	24	50.48	1961	21.30	1953	34.38
ALTON	3	38	66.94	1982	26.80	1976	45.55
ALTONA	4	3	46.03	1949	46.03	1949	46.03
AMITY	5	44	57.06	1973	18.69	1988	35.85
AMSTERDAM	6	4	41.57	1949	30.14	1950	35.86
ANDERSON	7	47	63.39	1973	21.74	1963	42.02
ANNAPOLIS 3 SW	8	30	72.19	1973	23.36	1953	44.63
APPLETON CITY	9	47	61.22	1951	21.46	1980	39.94
ARCADIA	10	76	74.23	1957	18.95	1953	44.09
ASH GROVE	11	17	64.84	1990	26.82	1989	43.29
ASHTON 1W	12	4	30.82	1949	25.87	1950	28.35
AUXVASSE 4 SSW	13	32	64.83	1969	22.79	1966	36.83
AVA RANGER STATION	14	24	60.59	1951	24.15	1953	40.38
BEDFORD 1 S	15	4	39.90	1949	20.99	1950	30.45
BELLEVIEW	16	47	65.91	1985	19.83	1953	42.71
BERNIE	17	47	77.82	1957	30.23	1980	47.97
BERRYMAN 6 NW	18	24	53.71	1968	24.03	1976	41.07
BETHANY	19	77	61.35	1993	18.44	1988	35.52
BILLINGS 2 N	20	33	62.91	1990	24.23	1980	42.78
BIRCH TREE	21	51	69.14	1927	26.13	1953	43.28
BLACK 6 NW	22	7	61.98	1951	26.23	1953	41.79
BLOOMFIELD	23	47	73.70	1957	27.62	1980	47.90
BLUE LICK	24	4	24.50	1949	21.20	1950	22.85
BOLIVAR 1 NE	25	70	66.32	1990	23.88	1980	41.19
BOONVILLE	26	3	47.88	1949	47.88	1949	47.88
BOONVILLE	27	47	74.67	1983	24.26	1956	41.22
BOWLING GREEN 2 NE	28	47	53.79	1973	25.48	1952	37.33
BRADLEYVILLE	29	4	53.10	1950	45.27	1949	49.19
BROOKFIELD	30	47	57.63	1973	23.36	1956	39.00
BROWNING 3 NE	31	3	43.53	1949	43.53	1949	43.53
BRUNSWICK	32	77	62.32	1961	19.42	1956	37.77
BUFFALO 3 S	33	47	64.14	1990	27.08	1953	41.61
BUICK TOWER	34	2	40.06	1956	40.06	1956	40.06
BUNKER	35	46	67.49	1973	25.93	1989	42.77
BURLINGTON JCT.	36	46	52.49	1973	24.92	1974	34.09
BUTLER	37	46	62.08	1973	22.08	1980	41.05
BUTLER FAA AP	38	12	57.44	1951	25.32	1953	35.89
BYNUMVILLE 1 E	39	12	46.5	1982	16.67	1988	35.48
CALIFORNIA	40	41	62.19	1993	23.23	1980	38.34
CAMDENTON	41	47	61.53	1990	25.2	1953	43.43
CAMPBELL	42	26	71.25	1927	31	1943	48.04
CANTON L AND D 20	43	47	59.81	1973	19.57	1956	36.7
CAP AU GRIS L & D 25	44	4	42.87	1949	31.71	1950	37.29
CAPE GIRARDEAU FAA AP	45	35	68.32	1973	29.91	1980	46.51
CAPE GIRARDEAU MO ST.	46	13	65.74	1950	28.87	1953	46.01
CAPE GIRARDEAU	47	22	62.53	1949	26.7	1953	44.57
CAPLINGER MILLS 1 N	48	47	65.11	1951	23.44	1963	39.92
CARROLLTON	49	47	60.8	1961	21.54	1956	39.89
CARTHAGE	50	43	51.45	1951	23.61	1963	39.49
CARUTHERSVILLE	51	77	76.18	1957	24.23	1963	48.04
CASSVILLE RANGER STN	52	50	59.57	1974	27.33	1953	44.32
CENTERVILLE	53	47	71.08	1985	22.78	1953	47.09
CENTERVILLE RANGER STN	54	13	72.36	1957	24.78	1953	49.72

Source: National Climatic Data Center

STATION NAME	Index	Years of record	Maximum (inches)	Year	Minimum (inches)	Year	Mean (inches)
CENTRALIA	55	47	56.34	1969	23.29	1980	35.74
CHADWICK	56	8	63.71	1951	36.30	1954	46.97
CHARLESTON	57	44	73.71	1957	33.19	1963	47.59
CHILLICOTHE	58	47	56.44	1993	20.07	1953	36.36
CHILLICOTHE RADIO KCHI	59	63	52.40	1961	21.63	1953	36.15
CLARKSVILLE L AND D 24	60	7	57.00	1993	24.39	1950	42.85
CLEARWATER DAM	61	47	67.63	1982	26.12	1953	44.21
CLIFTON CITY	62	47	60.71	1993	21.27	1953	38.80
CLIMAX SPRINGS	63	9	49.42	1974	24.18	1976	36.73
CLINTON	64	77	65.09	1993	23.85	1953	40.34
COLE CAMP 9 SE	65	25	59.75	1965	25.10	1976	42.67
COLOMA	66	46	53.21	1993	17.56	1956	36.16
COLUMBIA WB AP	67	22	47.64	1949	25.12	1953	34.24
COLUMBIA WSO AP	68	26	62.49	1993	23.66	1980	40.60
COLUMBIA WB CITY	69	4	50.15	1949	32.32	1950	41.24
COLUMBIA 9 WNW	70	6	52.79	1949	30.78	1950	40.66
CONCEPTION	71	47	62.44	1993	15.53	1988	35.76
CONCORDIA	72	47	62.65	1961	22.70	1956	40.14
COOK STATION	73	37	59.45	1951	17.76	1976	39.58
CRANE MOUNTAIN	74	27	69.25	1973	24.87	1953	43.12
CROCKER	75	25	61.78	1949	25.23	1953	39.82
CRYSTAL CITY	76	12	53.08	1951	22.27	1953	34.82
CUBA	77	16	55.70	1951	22.31	1953	36.85
DEERING	78	8	61.21	1950	35.75	1953	47.71
DE SOTO	79	40	62.45	1957	27.41	1976	39.71
DEXTER	80	39	77.41	1957	33.12	1980	48.46
DIAMOND	81	22	63.35	1985	31.72	1980	46.13
DONIPHAN	82	47	69.53	1957	31.37	1980	47.44
DONIPHAN 1 W	83	10	61.64	1950	29.63	1953	45.49
DORA	84	36	59.66	1985	25.03	1976	45.27
DOWNING	85	7	37.96	1949	27.52	1950	32.74
EAST END	86	12	38.15	1955	27.30	1953	33.90
EDGERTON	87	47	61.05	1965	22.43	1956	37.03
EDINA	88	47	54.95	1993	17.81	1988	35.72
ELDON	89	47	61.54	1993	24.29	1953	41.17
ELDORADO SPRINGS	90	45	64.52	1951	24.62	1980	42.75
ELIJAH	91	14	62.73	1949	27.6	1953	47.15
ELLINGTON	92	47	67.57	1951	26.59	1953	44.00
ELLSINORE	93	25	67.01	1957	33.09	1955	46.17
ELM	94	4	50.58	1993	45.55	1992	48.07
ELSBERRY 1 S	95	64	58.94	1993	24.83	1989	36.37
EMINENCE 5 WNW	96	4	48.82	1950	48.82	1950	48.82
EMINENCE 1 N	97	4	47.35	1992	47.35	1992	47.35
FAIRFAX	98	47	54.20	1993	18.81	1953	35.48
FARMINGTON	99	77	62.92	1957	24.81	1953	41.47
FARMINGTON FAA AP	100	12	62.96	1957	26.45	1953	44.00
FAYETTE	101	61	58.71	1973	23.27	1953	36.55
FAYETTE EXP LAGOON	102	6	48.70	1961	30.06	1959	37.23
FESTUS 2 NW	103	32	57.98	1993	20.77	1976	38.29
FISK	104	50	71.22	1972	27.38	1953	47.03
FORSYTH	105	5	46.25	1950	41.29	1949	43.77
FOUNTAIN GROVE WILDLIFE	106	34	55.64	1973	22.30	1956	37.13
FREDERICKTOWN	107	47	67.86	1957	23.19	1953	43.97
FREEDOM	108	33	71.82	1993	23.84	1980	40.04
FREMONT TOWER	109	12	66.02	1957	23.60	1953	43.13
FULTON	110	77	65.33	1993	21.87	1930	38.56
GALENA	111	47	66.04	1993	25.73	1980	43.23
GALLATIN	112	29	58.16	1993	22.29	1956	38.06

STATION NAME	Index	Years of record	Maximum (inches)	Year	Minimum (inches)	Year	Mean (inches)
GERALD	113	30	56.74	1949	23.25	1976	39.77
GOLDSBERRY	114	11	47.65	1970	24.47	1963	37.83
GRAHAM 1 NW	115	9	64.16	1993	32.75	1989	42.79
GRANBY	116	26	53.72	1957	19.16	1963	41.33
GRANT CITY	117	47	48.81	1993	15.26	1988	34.93
GREENVILLE 6 N	118	73	71.77	1945	23.71	1953	45.24
GREGORY LANDING	119	37	56.05	1982	18.83	1953	38.18
GROVESPRING	120	42	57.90	1951	23.40	1953	41.42
HAILEY 3 WSW	121	22	60.92	1957	25.94	1953	42.08
HAMDEN 2 NE	122	4	46.59	1949	30.39	1950	38.49
HAMILTON 2 W	123	41	56.82	1993	15.51	1964	35.51
HANNIBAL 1 N	124	18	48.38	1961	20.50	1953	34.01
HANNIBAL WATERWORKS	125	47	61.22	1981	20.59	1956	38.27
HARRIS	126	4	40.75	1949	34.36	1950	37.56
HARRISONVILLE	127	37	52.18	1961	21.33	1956	35.14
HAZELGREEN 1 W	128	31	60.78	1951	24.21	1953	38.20
HENRIETTA	129	3	26.53	1950	26.53	1950	26.53
HERMANN	130	47	62.81	1993	25.64	1989	38.76
HERMITAGE	131	24	56.26	1951	25.63	1953	39.66
HIGBEE 4 S	132	6	61.90	1993	24.51	1950	43.21
HIGH LOOKOUT	133	3	53.47	1949	53.47	1949	53.47
HIGH POINT 2 NE	134	4	51.74	1949	39.73	1950	45.74
HOLT 3 E	135	11	49.88	1985	32.40	1983	40.27
HORNERSVILLE	136	7	61.71	1950	46.96	1949	54.34
HOUSTON 3 E	137	43	61.31	1990	24.89	1976	42.30
HOUSTON 1 SE	138	4	60.40	1949	42.99	1950	51.70
HOUSTON 2 W	139	17	61.83	1990	31.41	1986	44.57
IBERIA 2 S	140	20	59.90	1993	30.10	1980	47.28
INDEPENDENCE	141	5	57.27	1993	35.20	1991	46.93
INDEPENDENCE 2	142	16	52.97	1985	38.95	1987	44.60
JACKSON	143	64	79.15	1945	28.22	1953	46.29
JEFFERSON CITY WTR PLT	144	77	66.13	1993	24.08	1953	39.85
JEFFERSON CITY	145	14	47.56	1949	18.44	1953	33.88
JEROME	146	42	55.51	1993	24.31	1962	41.11
JEWETT	147	4	57.40	1949	52.61	1950	55.01
JOPLIN FAA AP	148	47	65.25	1985	18.35	1963	42.29
KAHOKA	149	33	53.98	1970	24.25	1953	37.46
KANSAS CITY WSO AP	150	23	55.26	1973	23.68	1976	38.89
KANSAS CITY FSS	151	39	60.25	1961	20.93	1953	36.01
K C GREEN HAVEN WEST	152	11	59.66	1961	28.08	1963	38.34
K C MO 75TH & HOLMES	153	4	42.03	1949	26.72	1950	34.38
KANSAS CITY U OF MO	154	23	45.79	1951	19.27	1953	31.92
KENNETT RADIO KBOA	155	42	86.75	1957	25.37	1963	49.84
KEYTESVILLE 4 NE	156	6	45.45	1949	27.32	1950	36.74
KIDDER	157	36	48.95	1947	26.66	1933	36.36
KING CITY	158	45	62.16	1993	19.49	1988	37.21
KINGSVILLE 5 SSW	159	14	57.53	1993	26.45	1988	46.65
KIRKSVILLE RADIO KIRX	160	77	52.67	1947	15.91	1988	36.68
KIRKSVILLE FAA AP	161	26	47.51	1969	24.66	1953	34.81
KNOXVILLE 2 SSE	162	3	22.66	1950	22.66	1950	22.66
KOSHKONONG	163	43	73.95	1945	26.33	1953	46.68
LABELLE	164	47	51.63	1970	14.97	1988	36.26
LAKESIDE	165	47	58.31	1985	23.91	1953	39.84
LAMAR	166	47	71.07	1992	21.45	1953	43.62
LAMPE FOREST SERVICE	167	13	58.49	1957	26.77	1953	44.59
LAMPE 4 NNE	168	4	53.02	1950	47.54	1949	50.28
LATHROP	169	18	53.25	1951	26.07	1956	37.06
LEBANON 2 W	170	77	74.20	1927	25.51	1963	42.51

STATION NAME	Index	Years of record	Maximum (inches)	Year	Minimum (inches)	Year	Mean (inches)
LEEPER	171	6	57.94	1950	38.08	1952	51.52
LEES SUMMIT 2 NNW	172	3	26.65	1950	26.65	1950	26.65
LEES SUMMIT REED WLR	173	33	55.93	1993	21.06	1963	40.15
LEXINGTON 3 NE	174	77	58.12	1961	21.05	1976	37.74
LICKING 4 N	175	47	64.72	1985	20.96	1953	42.36
LINNEUS	176	23	47.89	1961	21.75	1950	35.44
LIVONIA	177	4	41.70	1949	27.35	1950	34.53
LOCKWOOD	178	77	65.58	1927	23.11	1980	43.66
LONG BRANCH RESERVOIR	179	6	58.09	1993	39.24	1992	46.49
LOUISIANA STARKS NUR	180	69	61.99	1926	24.11	1971	37.98
LOUISIANA	181	47	51.64	1970	25.17	1989	37.67
LUCERNE	182	35	49.49	1961	22.54	1966	33.35
MACEDONIA LOOKOUT	183	10	63.68	1949	24.86	1953	43.34
MACON	184	37	55.95	1969	24.37	1953	38.26
MADISON	185	42	60.91	1973	21.86	1953	36.86
MALDEN FAA AIRPORT	186	13	74.60	1957	30.63	1955	45.25
MALDEN MUNICIPAL AP	187	35	57.61	1975	30.83	1963	45.76
MANSFIELD	188	45	62.79	1951	26.01	1953	44.30
MARBLE HILL	189	47	72.83	1957	27.17	1953	47.13
MARSHALL	190	44	59.73	1973	24.64	1966	37.01
MARSHFIELD	191	47	61.64	1990	20.90	1953	42.18
MARTINSBURG	192	39	57.89	1969	24.04	1963	38.10
MARYVILLE 2 E	193	77	63.45	1993	21.54	1971	35.05
MARYVILLE 7 NNW	194	4	36.57	1949	30.02	1950	33.30
MC CREDIE 2 W	195	4	45.26	1949	27.74	1950	36.50
MC CREDIE EXP STN	196	4	46.01	1949	25.08	1950	35.55
MEMPHIS	197	47	61.87	1970	23.23	1953	34.33
MERCER 6 NW	198	28	55.34	1961	24.93	1953	34.52
MEXICO	199	47	65.32	1969	25.37	1989	39.06
MIDDLETOWN 5 ENE	200	25	52.56	1969	22.49	1953	34.57
MILAN	201	47	61.39	1993	20.01	1988	37.41
MOBERLY RADIO KWIX	202	59	60.32	1993	22.08	1988	36.80
MONETT	203	24	55.58	1957	22.25	1953	40.04
MONETT WSMO	204	23	62.77	1990	27.48	1980	47.38
MONROE CITY	205	42	61.13	1973	23.50	1950	39.10
MORA	206	4	43.94	1949	32.71	1950	38.33
MOREHOUSE	207	25	74.85	1957	30.96	1953	45.42
MOSELLE	208	23	67.08	1957	29.01	1954	38.46
MOUNTAIN GROVE 2 N	209	77	72.88	1927	20.43	1953	42.98
MOUNTAIN VIEW 2 SW	210	9	51.43	1993	42.15	1989	47.03
MOUNT VERNON 3 SW	211	31	55.33	1957	25.06	1953	40.11
MT VERNON M U SW CTR	212	34	61.01	1993	29.00	1980	44.10
NEOSHO	213	77	66.07	1973	20.46	1963	44.24
NEVADA SEWAGE PLANT	214	77	61.18	1961	24.96	1930	41.52
NEW BOSTON 3 NE	215	14	41.51	1951	24.22	1953	32.44
NEW FLORENCE	216	31	51.54	1969	22.42	1963	37.59
NEW FLORENCE 2	217	10	67.11	1982	27.88	1988	44.09
NEW FRANKLIN 1 W	218	39	55.21	1993	22.67	1980	37.95
NEW MADRID	219	18	84.61	1957	31.72	1963	49.08
NEW MADRID	220	32	71.24	1990	34.83	1980	50.65
NOVINGER	221	5	39.80	1949	31.67	1950	35.74
OATES TOWER	222	4	52.94	1949	52.94	1949	52.94
ODESSA	223	47	56.89	1973	20.51	1956	39.47
OLDFIELD	224	31	72.82	1993	25.58	1962	45.83
OREGON	225	40	60.49	1973	17.56	1953	35.40
OSCEOLA	226	40	53.34	1974	23.82	1976	40.45
OSCEOLA 3 NE	227	9	56.28	1951	24.64	1953	37.65
OWENSVILLE	228	31	50.51	1978	25.30	1976	39.52

STATION NAME	Index	Years of record	Maximum (inches)	Year	Minimum (inches)	Year	Mean (inches)
OZARK	229	47	60.81	1993	25.63	1980	43.33
OZARK BEACH	230	46	58.83	1968	26.44	1980	42.58
PACIFIC	231	47	63.43	1957	22.92	1976	38.47
PALMYRA	232	47	54.77	1973	19.88	1988	36.71
PARIS	233	39	59.89	1973	24.89	1963	38.74
PARMA	234	47	79.38	1957	27.27	1980	46.18
PATTONSBURG 2 S	235	19	57.99	1993	19.65	1988	36.03
PERRYVILLE WATER PLT	236	46	58.37	1957	25.32	1953	41.30
PIERCE CITY	237	47	63.51	1973	26.06	1963	42.38
PIERCE CITY 4 NNE	238	4	52.46	1957	37.46	1958	47.24
PLATTSBURG	239	24	64.57	1973	24.52	1988	39.51
PLEASANT HILL	240	25	65.17	1961	29.07	1963	44.55
POLK 2 NE	241	5	51.20	1993	35.41	1992	43.31
POLO	242	47	55.64	1993	18.71	1956	37.66
POMME DE TERRE DAM	243	34	55.19	1973	21.76	1980	39.27
POPLAR BLUFF R S	244	77	77.76	1927	27.53	1953	46.78
PORTAGEVILLE	245	14	86.45	1957	28.03	1963	47.18
PORTAGEVILLE	246	29	77.44	1973	38.56	1981	48.95
POTOSI 2 S	247	16	50.32	1949	34.10	1988	42.05
PRAIRIE HILL 3 WNW	248	13	52.26	1961	22.83	1956	36.03
PRINCETON 6 SW	249	42	59.45	1993	18.41	1988	35.32
PUXICO	250	43	80.07	1973	28.24	1953	47.76
QULIN	251	47	67.47	1957	26.70	1980	45.64
REYNOLDS	252	37	68.18	1957	21.60	1953	42.33
RICH FOUNTAIN 3 E	253	8	72.87	1993	27.65	1989	43.68
RICHWOODS	254	4	62.23	1957	23.35	1976	36.57
RIDGEWAY 8 NW	255	4	30.29	1949	30.29	1949	30.29
ROBY	256	31	64.05	1951	21.57	1953	40.76
ROGERSVILLE	257	4	42.26	1950	42.26	1950	42.26
ROLLA UNIV OF MO	258	76	69.42	1985	24.56	1953	41.89
ROLLA 5 SE	259	4	50.35	1949	45.17	1950	47.76
ROLLA 3 W	260	4	55.45	1949	47.62	1950	51.54
ROLLA 4 SE	261	4	51.40	1949	44.83	1950	48.12
ROLLA 7 S	262	4	51.93	1949	43.07	1950	47.50
ROSEBUD	263	15	73.53	1993	31.82	1989	46.63
ROUND SPRING R S	264	47	60.88	1985	20.04	1953	42.44
SAINT CHARLES	265	77	58.68	1993	19.06	1930	37.03
ST CHARLES 7 SSW	266	20	50.52	1990	24.04	1976	38.02
ST JAMES 3 NW	267	4	60.15	1949	43.62	1950	51.89
ST JOSEPH 4 WNW	268	30	55.60	1973	20.74	1966	34.51
SAINT JOSEPH WB AP	269	17	53.99	1951	21.81	1953	34.94
ST LOUIS SCIENCE CENTER	270	19	53.13	1993	24.82	1976	39.58
SAINT LOUIS WSCMO AP	271	54	54.97	1982	20.59	1953	36.70
SAINT LOUIS-EADS BR	272	28	52.72	1957	22.98	1953	35.07
SAINT LOUIS UNIVERSITY	273	25	51.95	1957	24.11	1953	36.29
SAINT LOUIS WASH UNIV	274	10	46.01	1949	24.98	1953	35.89
SAINT LOUIS WSFO	275	15	49.73	1985	27.90	1980	38.73
SALEM	276	77	63.75	1945	19.01	1953	42.14
SALISBURY	277	47	61.12	1993	21.82	1956	39.51
SAVERTON L AND D 22	278	47	53.16	1981	18.48	1953	36.30
SEDALIA WATER PLANT	279	58	60.37	1969	22.14	1956	40.15
SELIGMAN	280	70	64.03	1985	23.52	1963	43.16
SENECA	281	11	42.69	1949	35.97	1991	39.65
SEYMOUR 1 NNW	282	13	54.72	1951	27.85	1954	41.56
SHELBINA	283	47	58.97	1973	18.95	1988	37.55
SHELBYVILLE	284	26	53.96	1969	24.66	1956	37.08
SIKESTON	285	34	80.71	1927	32.87	1953	48.08
SIKESTON POWER STATION	286	40	83.54	1957	29.59	1980	45.67

STATION NAME	Index	Years of record	Maximum (inches)	Year	Minimum (inches)	Year	Mean (inches)
SILOAM SPRINGS	287	47	55.80	1993	22.64	1953	42.26
SKIDMORE	288	4	35.37	1949	33.72	1950	34.55
SMITHVILLE LAKE	289	14	52.51	1993	26.94	1991	42.49
SPEED 2 NW	290	4	60.72	1949	33.76	1950	47.24
SPICKARD 7 W	291	38	57.38	1961	15.88	1988	38.14
SPRING CITY	292	4	47.40	1949	46.85	1950	47.13
SPRINGFIELD WSO AP	293	47	63.19	1990	25.21	1953	42.02
STANBERRY	294	5	30.88	1950	30.88	1950	30.88
STEELVILLE 2 N	295	47	66.08	1993	23.51	1976	39.80
STEFFENVILLE	296	77	57.75	1973	18.46	1988	36.91
STET 4 SSE	297	6	56.29	1993	56.29	1993	56.29
STOCKTON DAM	298	25	59.65	1992	23.37	1980	42.86
STOVER	299	42	63.03	1993	21.98	1953	39.99
SULLIVAN 3 SE	300	42	59.88	1957	22.22	1953	41.13
SUMMERSVILLE	301	47	65.12	1973	21.62	1953	42.99
SUMNER 3 WSW	302	37	57.90	1973	18.15	1956	35.76
SWEET SPRINGS	303	47	61.92	1951	22.69	1956	38.72
TARKIO	304	75	60.55	1973	14.74	1988	33.85
TECUMSEH	305	47	59.84	1993	23.14	1980	44.08
TOPAZ 4 NE	306	22	54.93	1957	20.31	1953	41.51
TRENTON	307	70	54.41	1982	22.98	1936	36.38
TROY	308	47	60.94	1993	23.10	1952	37.79
TRUMAN DAM & RESERVOIR	309	15	57.64	1985	31.39	1991	42.78
TYRONE 2 NNW	310	3	43.48	1950	43.48	1950	43.48
UNION	311	47	66.85	1993	22.58	1976	39.40
UNIONVILLE	312	74	54.49	1928	21.68	1956	36.63
UNITY VILLAGE	313	14	59.66	1982	29.35	1988	43.19
VALLEY PARK	314	47	64.63	1993	22.00	1953	40.40
VAN BUREN	315	38	79.16	1982	29.82	1955	46.02
VAN BUREN RANGER STN	316	32	75.41	1982	29.51	1980	46.68
VANDALIA	317	44	66.66	1993	23.58	1963	40.50
VANZANT 4 SE	318	12	55.10	1951	23.63	1953	43.12
VERSAILLES	319	45	56.47	1990	27.22	1962	40.16
VICHY 2 SE	320	4	54.70	1949	45.61	1950	50.16
VICHY FAA AP	321	41	59.84	1993	23.12	1953	38.93
VIENNA 2 WNW	322	36	63.06	1993	28.03	1962	42.33
VILLA RIDGE 2 NW	323	4	41.87	1950	41.87	1950	41.87
WACO 2 E	324	47	64.87	1985	22.50	1963	41.04
WAPPAPELLO DAM	325	47	78.61	1973	27.76	1953	45.94
WARRENSBURG	326	75	63.06	1985	21.13	1956	38.73
WARRENSBURG 4 E	327	4	43.88	1949	32.45	1950	38.17
WARRENTON 1 N	328	76	64.02	1993	22.89	1930	37.75
WARSAW 1	329	67	61.12	1921	26.55	1956	42.60
WARSAW 2	330	13	62.32	1951	22.57	1953	37.61
WASHINGTON 2	331	6	43.65	1950	43.47	1949	43.56
WASOLA	332	47	62.23	1973	21.76	1953	39.39
WAVERLY	333	39	47.23	1967	22.18	1953	31.95
WAYNESVILLE 2 W	334	46	66.65	1985	24.95	1976	42.07
WEBSTER GROVES	335	27	64.87	1957	26.71	1952	38.43
WEINGARTEN	336	17	53.13	1949	28.01	1953	38.57
WELDON SPRING WLDLF A	337	38	46.87	1969	23.19	1976	34.40
WEST PLAINS	338	47	65.37	1973	23.87	1953	44.89
WILLIAMSBURG 2 WSW	339	4	27.08	1950	27.08	1950	27.08
WILLIAMSVILLE	340	47	68.64	1982	28.63	1953	45.58
WILLOW SPRGS RADIO KUKU	341	47	59.72	1984	24.55	1953	44.28
WILLOW SPRINGS FOREST S	342	4	53.38	1949	53.38	1949	53.38
WINDSOR	343	46	63.52	1973	24.50	1976	39.81
ZALMA 4 E	344	47	69.44	1973	26.10	1953	46.21

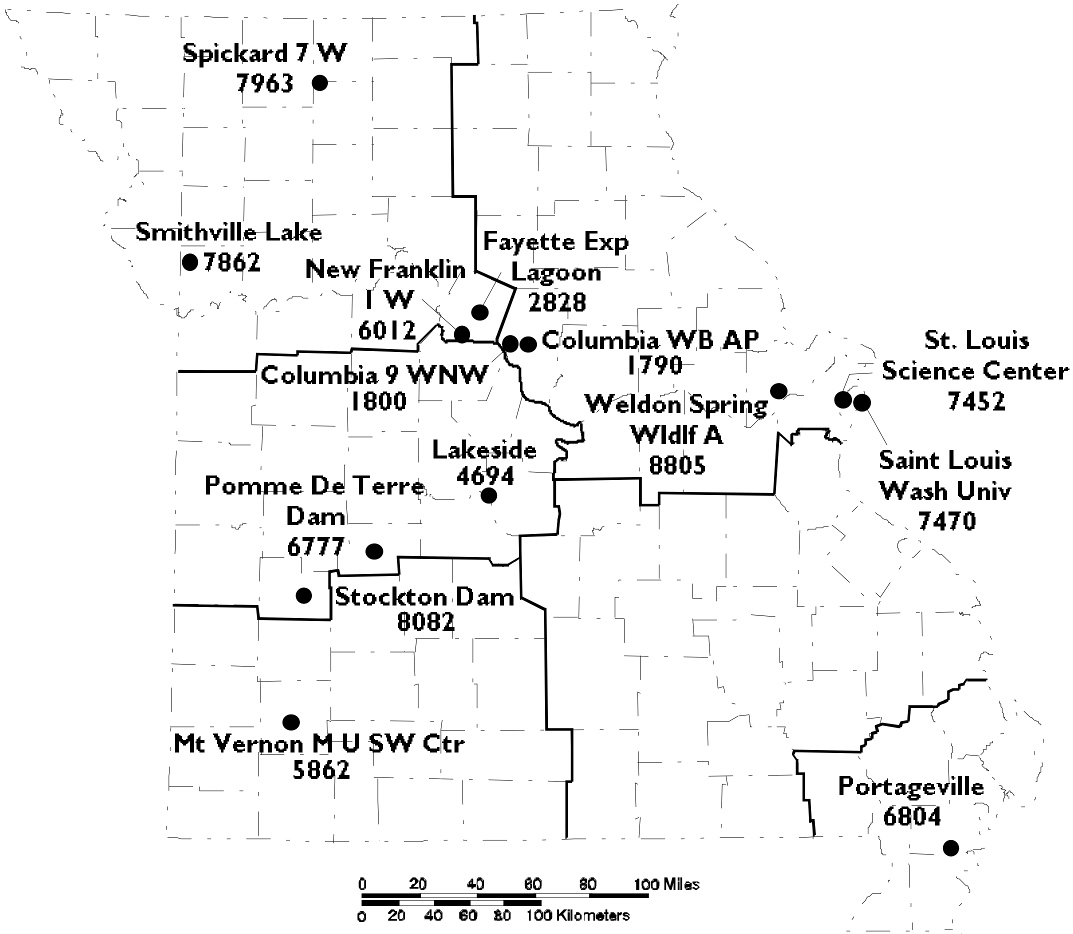
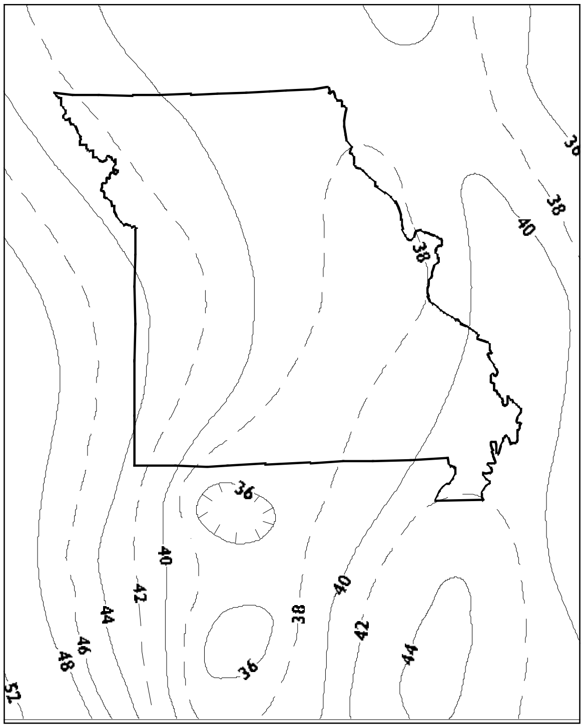


Figure 7. Evaporation station locations. (Source: National Climatic Data Center)

Table 2. Evaporation stations in Missouri

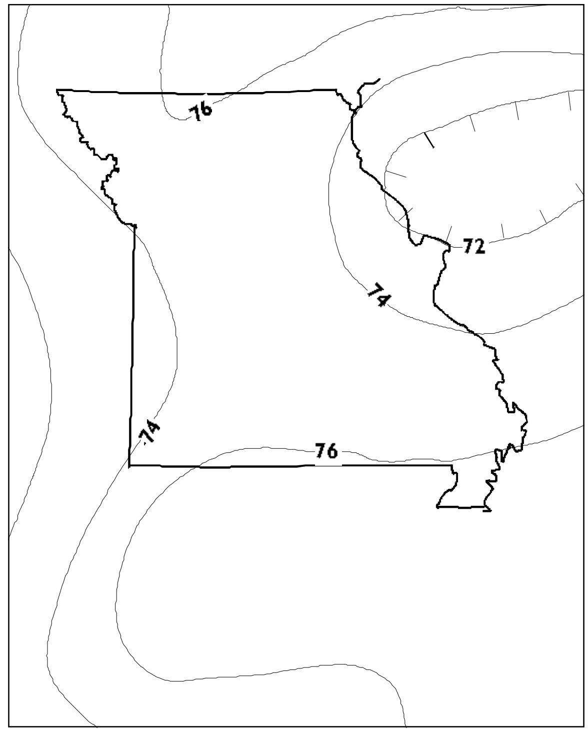
Station ID	Station Name	Begining year	Ending year	Total years	Coverage
1790	COLUMBIA WB AP	1953	1955	3	57.81%
1800	COLUMBIA 9 WNW	1948	1952	5	52.38%
2828	FAYETTE EXP LAGOON	1957	1962	6	45.60%
4694	LAKESIDE	1948	1990	43	68.98%
5862	MT VERNON M U SW CTR	1963	1995	28	44.87%
6012	NEW FRANKLIN 1 W	1956	1995	40	45.65%
6777	POMME DE TERRE DAM	1961	1995	22	51.71%
6804	PORTAGEVILLE	1992	1995	4	50.65%
7452	ST LOUIS SCIENCE CENTER	1990	1995	6	40.76%
7470	SAINT LOUIS WASH UNIV	1948	1957	10	48.23%
7862	SMITHVILLE LAKE	1985	1995	11	47.10%
7963	SPICKARD 7 W	1957	1993	37	49.66%
8082	STOCKTON DAM	1970	1978	9	53.33%
8805	WELDON SPRING WLDLF A	1957	1981	20	46.55%

Source: National Climatic Data Center



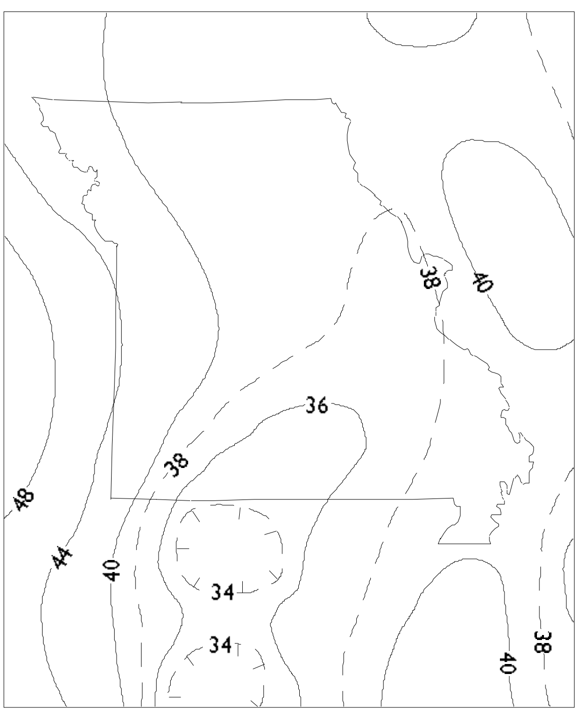
Sources: National Weather Service and the NOAA Technical Report NWS 33

Figure 8. Annual free water surface evaporation (shallow lake).



Sources: National Weather Service and the NOAA Technical Report NWS 33

Figure 10. May-October coefficients to convert class A pan evaporation to free water surface evaporation.



Sources: National Weather Service and the NOAA Technical Report NWS 33

Figure 9. May-October class A pan evaporation.

coefficients (Farmsworth, 1982,). The average annual free water surface evaporation varies from about 38 inches to about 44 inches. May through October pan evaporation varies from about 36 inches to 44 inches and pan coefficients range from about 0.74 to 0.76.

Evaporation varies from month to month with the highest evaporation occurring during the summer. Figure 11 shows the difference in median monthly pan evaporation for the Lakeside station. In this example, the highest evaporation is in July and lowest in December. There is also great variation in annual evaporation. In the 1950s the state experienced an extended drought with lower annual precipitation and higher temperature. Figure 12 shows the evaporation rates in 1952, 1953, 1954 and long-term 50% exceedance during May to October at the Lakeside station. The evaporation rate was above normal throughout these years. The rate was much below normal during 1993, when the region experienced an extremely wet year.

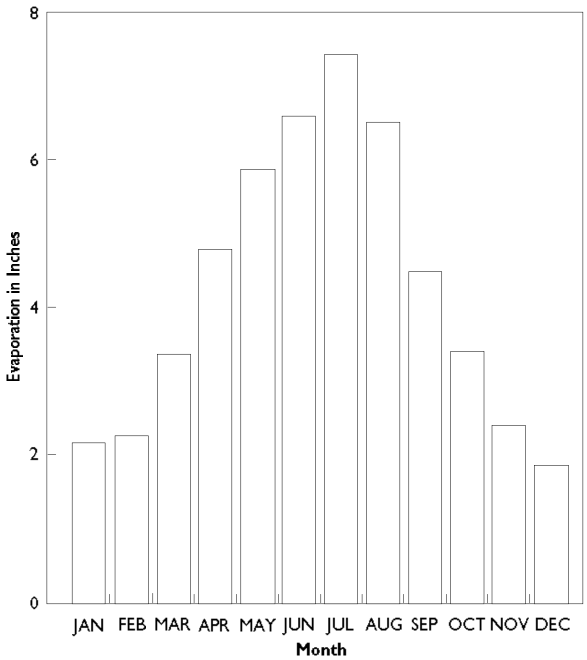


Figure 11. Pan evaporation at Lakeside station - median 1948-1990.

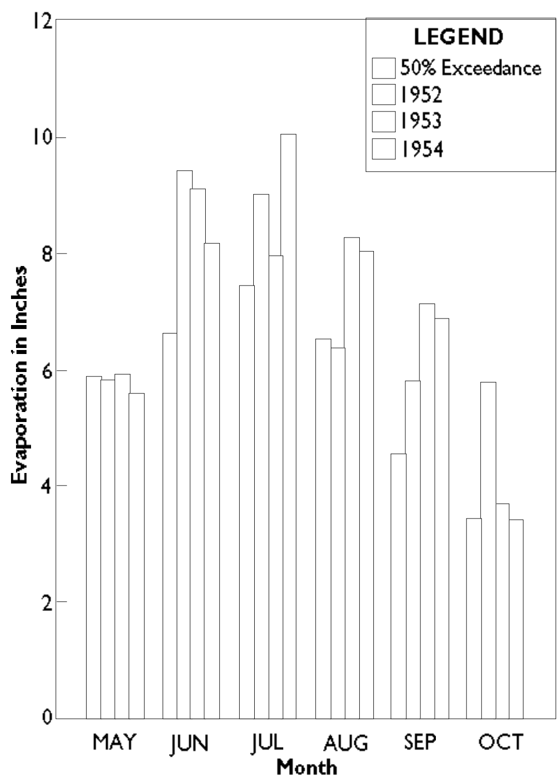


Figure 12. Lakeside evaporation comparison.

STREAMFLOW

Streamflow is another important component in the water balance equation. During dry periods the flow of streams is not governed by precipitation but by release of water from groundwater or surface water storage (i.e., reservoirs or wetlands). The low-flow characteristics of a stream determines the physical and economic viability of its utilization.

Runoff and streamflow tend to be quite variable during drought. There are not presently any reliable methods that give precise predictions of streamflow during drought at ungaged sites. This is because there seems to be great variability among sites. There are also not very reliable methods for predicting runoff during drought periods. Most of the methods predict runoff from a single event and don't perform well over a period of months. Streamflow and runoff prediction related to drought are areas with a great need for further research.

The U.S. Geological Survey collects and publishes streamflow data for Missouri. Figure 13 through 18 show the locations of the unregulated stream gages with more than 20 years records in the State. (The list of the gaging station names on unregulated streams was provided by Loyd Waite at U.S. Geological Survey.)

The magnitude, duration, and recurrence interval of low flows can be performed on streamflow data collected at stream gages. A common duration used is 7 days, and common recurrence interval is 10 years (7-day Q_{10}). Low flow statistics have been computed for gaging stations on unregulated streams with more than 20 years records (Table 3). This analysis was conducted using streamflow data from Hydrosphere Inc. and the Durfreak software. Durfreak allows the user to create Log-Pearson Type III duration-frequency analyses.

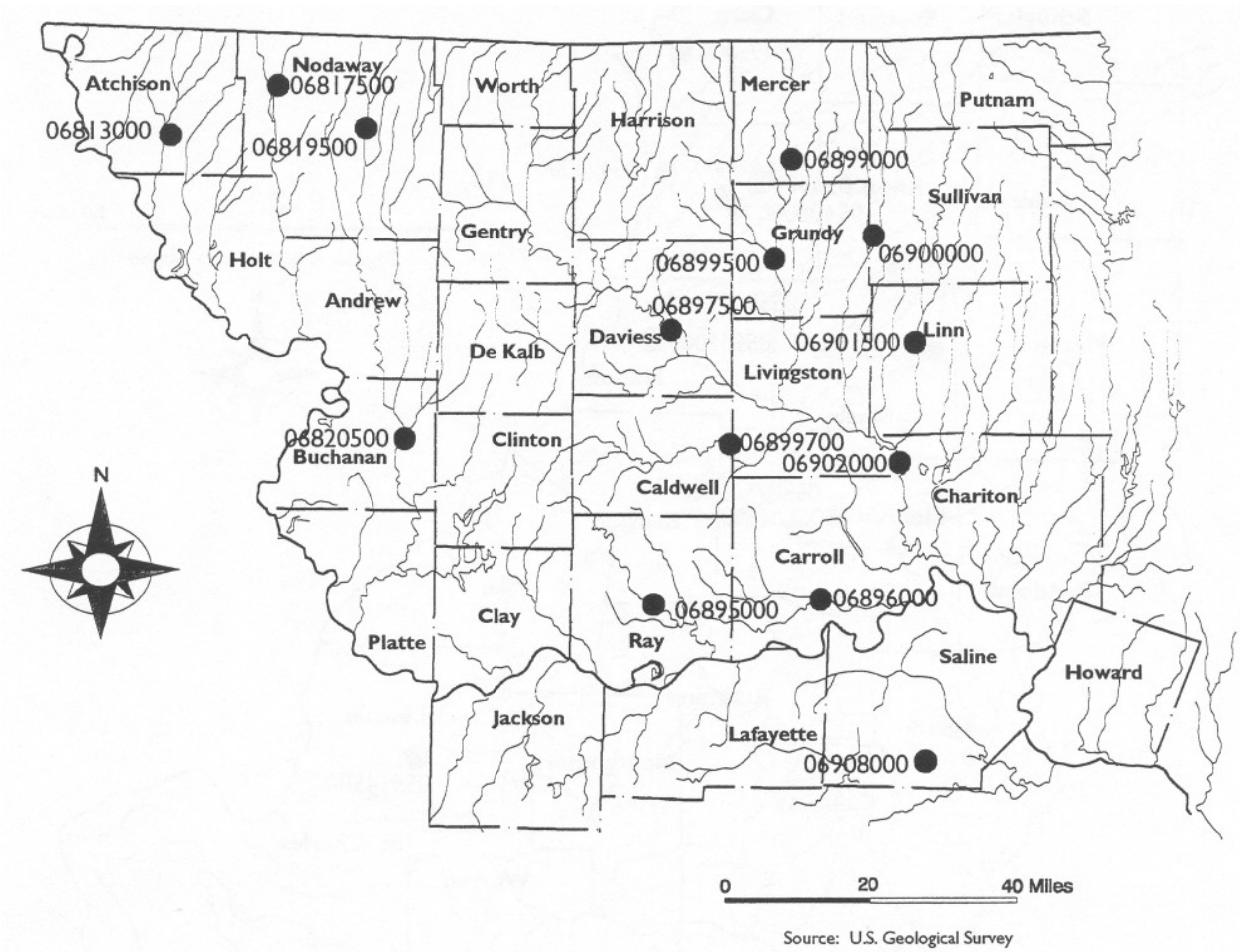


Figure 13. Gaging stations on unregulated streams, Region 1 (Northwest Prairie).

Figure 14. Gaging stations on unregulated streams, Region 2 (Northeast Prairie).

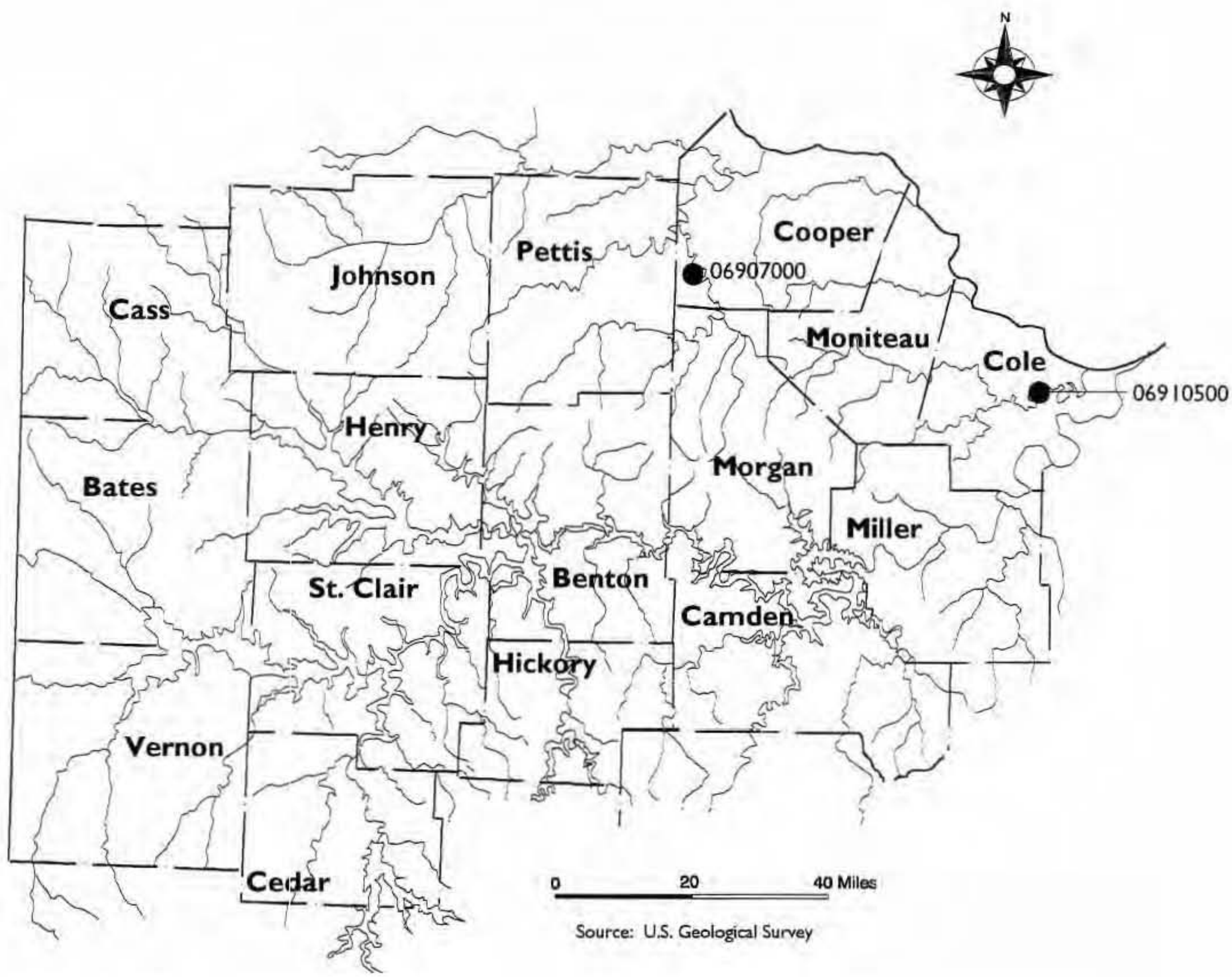


Figure 15. Gaging stations on unregulated streams, Region 3 (West Central Plains).

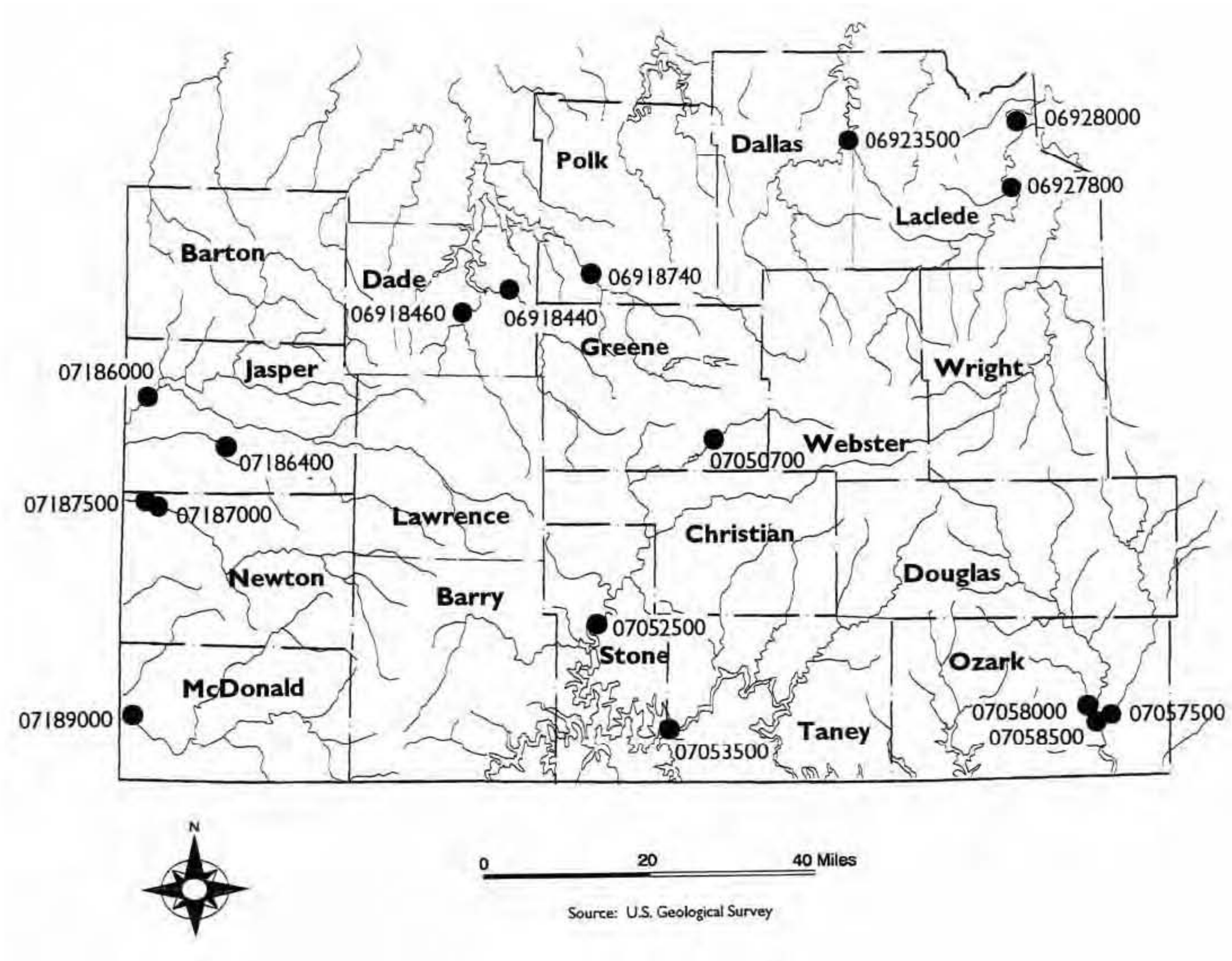


Figure 16. Gaging stations on unregulated streams, Region 4 (West Ozarks).

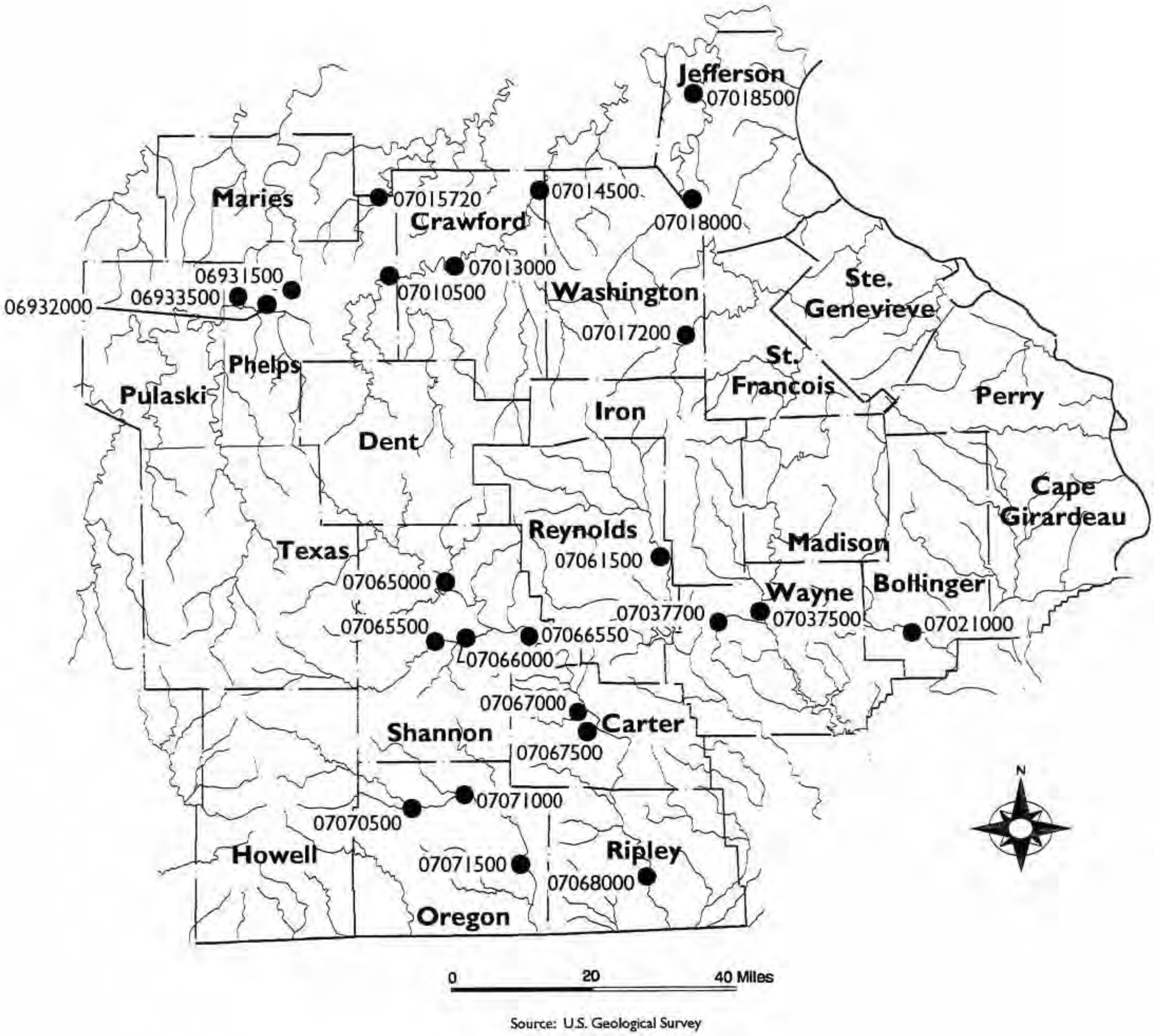


Figure 17. Gaging stations on unregulated streams, Region 5 (East Ozarks).

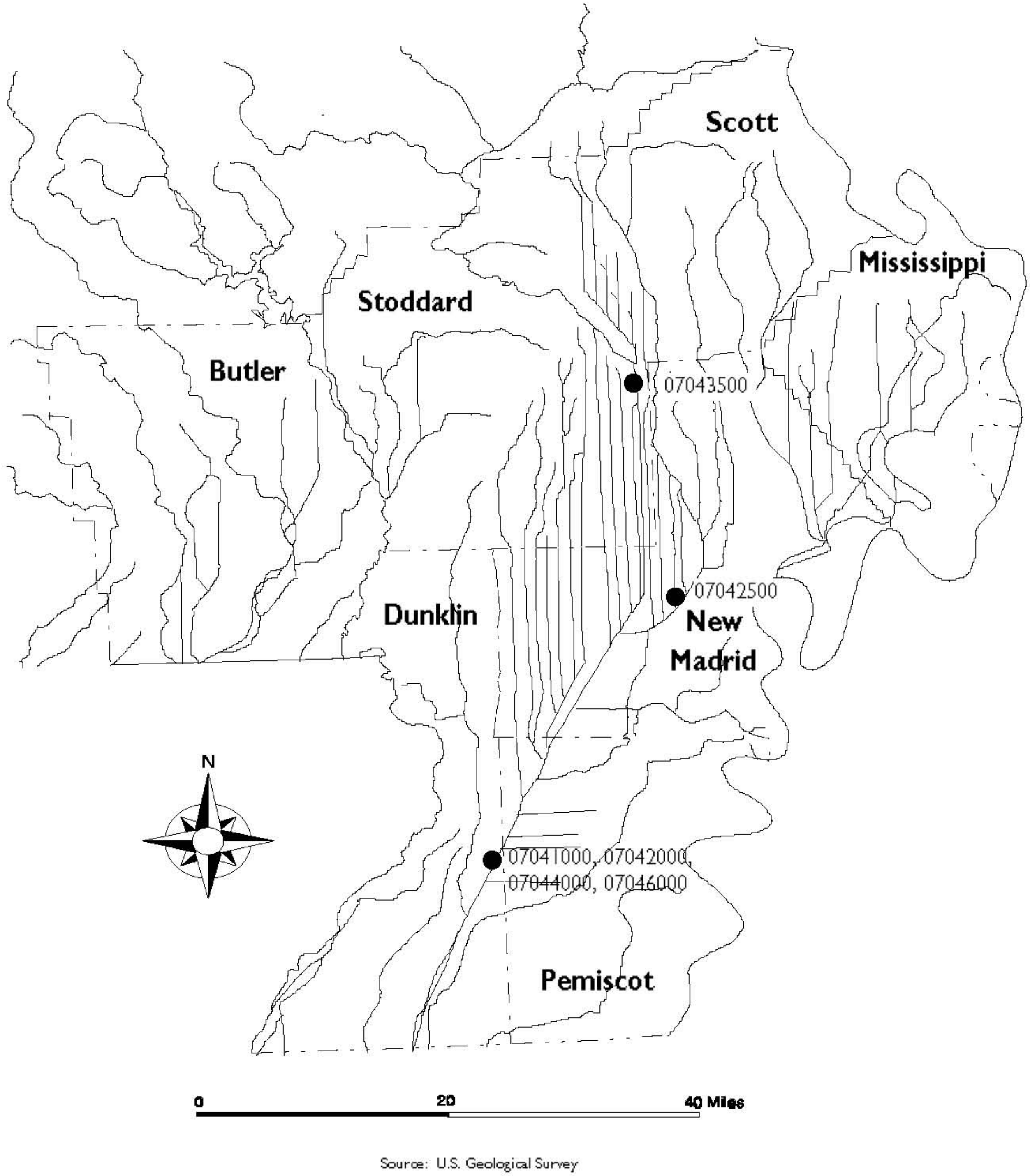


Figure 18. Gaging stations on unregulated streams, Region 6 (Bootheel).

Table 3. Seven-day low flow for gaging stations on unregulated streams with more than 20 years of records.

STATION-ID	STATION NAME	DRAINAGE AREA (in sq. mi.)	7-day low-flow (in cubic feet per second) for indicated recurrence interval (in years) 2	5	10	20	50
5495000	FOX RIVER AT WAYLAND, MO.	400	1.6	0.4	0.2	0.1	0.0
5496000	WYACONDA RIVER ABOVE CANTON, MO	393	1.9	0.6	0.3	0.1	0.1
5497000	NORTH FABIUS RIVER AT MONTICELLO, MO	452	3.7	1.3	0.7	0.4	0.2
5498000	MIDDLE FABIUS RIVER NEAR MONTICELLO, MO.	393	2.4	0.6	0.3	0.1	0.0
5500000	SOUTH FABIUS RIVER NEAR TAYLOR, MO	620	2.6	0.7	0.3	0.2	0.1
5501000	NORTH RIVER AT PALMYRA, MO	373	2.0	0.6	0.3	0.2	0.1
5502300	SALT RIVER AT HAGERS GROVE, MO.	365	2.4	1.1	0.7	0.5	0.4
5506500	MIDDLE FORK SALT RIVER AT PARIS, MO.	356	1.2	0.4	0.2	0.1	0.0
5506800	ELK FORK SALT RIVER NEAR MADISON, MO.	200	0.6	0.2	0.1	0.1	0.0
5507500	SALT RIVER NEAR MONROE CITY, MO.	2230	10	2.9	1.3	0.6	0.3
5514500	CUIVRE RIVER NEAR TROY, MO	903	4.1	1.2	0.6	0.3	0.1
6813000	TARKIO RIVER AT FAIRFAX MO	508	10	2.6	1.2	0.6	0.3
6817500	NODAWAY RIVER NEAR BURLINGTON JCT., MO	1240	25	11	7.4	5.1	3.3
6819500	ONE HUNDRED AND TWO RIVER AT MARYVILLE, MO	515	2.5	0.7	0.3	0.2	0.1
6820500	PLATTE RIVER NEAR AGENCY, MO.	1760	21	6.3	3.1	1.6	0.7
6895000	CROOKED RIVER NEAR RICHMOND, MO.	159	0.6	0.1	0.1	0.0	0.0
6896000	WAKENDA CREEK AT CARROLLTON, MO.	248	1.8	0.8	0.5	0.3	0.2
6897500	GRAND RIVER NEAR GALLATIN MO	2250	25	10	6.4	4.2	2.5
6899000	WELDON RIVER AT MILL GROVE MO	494	2.7	0.7	0.3	0.1	0.0
6899500	THOMPSON RIVER AT TRENTON MO	1670	28	11	6.6	4.2	2.5
6899700	SHOAL CREEK NEAR BRAYMER MO	391	1.4	0.4	0.2	0.2	0.1
6900000	MEDICINE CREEK NEAR GALT, MO	225	2.3	0.7	0.4	0.2	0.1
6901500	LOCUST CREEK NEAR LINNEUS, MO	550	3.9	1.7	1.1	0.7	0.4
6902000	GRAND RIVER NEAR SUMNER MO	6880	118	57	38	27	18
6907000	LAMINE RIVER AT CLIFTON CITY, MO.	598	3.4	1.1	0.6	0.3	0.2
6908000	BLACKWATER RIVER AT BLUE LICK, MO	1120	2.3	0.8	0.5	0.3	0.2
6910500	MOREAU RIVER NEAR JEFFERSON CITY, MO	561	3.4	1.1	0.6	0.3	0.2
6918440	SAC RIVER NEAR DADEVILLE, MO	257	18	12	9.7	8.2	6.9
6918460	TURNBACK CREEK ABOVE GREENFIELD, MO	252	26	19	16	14	12
6918740	LITTLE SAC RIVER NEAR MORRISVILLE, MO	237	8.9	5.6	4.1	3.1	2.2
6923500	BENNETT SPRING AT BENNETT SPRINGS, MO	100	89	76	70	66	62
6927000	MARIES RIVER AT WESTPHALIA, MO.	257	1.7	0.5	0.3	0.2	0.1
6927800	OSAGE FORK GASCONADE RIVER AT DRYNOB, MO.	404	24	19	17	16	15
6928000	GASCONADE RIVER NEAR HAZLEGREEN, MO	1250	67	42	32	26	20
6931500	LITTLE BEAVER CR NR ROLLA, MO	6.4	0.2	0.1	0.1	0.0	0.0
6932000	LITTLE PINEY CREEK AT NEWBURG, MO	200	44	34	30	26	23
6933500	GASCONADE RIVER AT JEROME MO	2840	490	392	351	321	291
6934000	GASCONADE RIVER NEAR RICH FOUNTAIN, MO.	3180	509	394	350	321	294
7010500	MARAMEC SPRING NEAR ST. JAMES	0.0	79	65	60	56	52
7013000	MERAMEC RIVER NEAR STEELVILLE, MO	781	131	106	95	87	79
7014500	MERAMEC RIVER NEAR SULLIVAN, MO.	1475	266	207	181	161	141
7015720	BOURBEUSE RIVER NR HIGH GATE MO	135	0.3	0.1	0.1	0.1	0.0
7016500	BOURBEUSE RIVER AT UNION, MO	808	33	24	21	18	16
7017200	BIG RIVER AT IRONDALE, MO	175	7.2	4.8	4.0	3.4	2.8
7018000	BIG RIVER NEAR DESOTO, MO	718	82	54	43	35	27
7018500	BIG RIVER AT BYRNESVILLE	917	100	71	59	51	42
7019000	MERAMEC RIVER NEAR EUREKA, MO	3788	460	347	300	266	232

STATION-ID	STATION NAME	DRAINAGE AREA (in sq. mi.)	7-day low-flow (in cubic feet per second) for indicated recurrence interval (in years) 2	5	10	20	50
7021000	CASTOR RIVER AT ZALMA, MO	423	48	35	30	25	21
7037500	ST. FRANCIS RIVER NEAR PATTERSON, MO	956	34	21	16	14	11
7037700	CLARK CREEK NEAR PIEDMONT MO	4.4	0.5	0.4	0.3	0.3	0.3
7041000	LITTLE RIVER DITCH 81 NEAR KENNETT MO	111	43	27	20	16	11
7042000	LITTLE RIVER DITCH 1 NEAR KENNETT MO	235	38	24	19	15	12
7042500	LITTLE RIVER DITCH 251 NEAR LILBOURN, MO.	235	72	50	41	35	29
7043500	LITTLE RIVER DITCH NO 1 NEAR MOREHOUSE, MO.	450	71	50	41	34	27
7044000	LITTLE RIVER DITCH 251 NEAR KENNETT MO	883	113	69	53	41	31
7046000	LITTLE RIVER DITCH 259 NEAR KENNETT MO	89	3.8	0.9	0.4	0.2	0.1
7050700	JAMES RIVER NEAR SPRINGFIELD, MO.	246	9.5	4.7	2.9	1.8	1.0
7052500	JAMES RIVER AT GALENA, MO	987	108	66	48	36	24
7053500	WHITE RIVER NEAR BRANSON, MO.	4022	180	70	41	26	15
7057500	NORTH FORK RIVER NEAR TECUMSEH, MO	561	296	251	230	213	196
7058000	BRYANT CREEK NEAR TECUMSEH, MO	570	144	122	112	105	97
7058500	NORTH FORK RIVER AT TECUMSEH	1157	435	372	351	337	326
7061500	BLACK RIVER NEAR NEAR ANNAPOLIS, MO	484	102	84	78	73	69
7065000	ROUND SPRING AT ROUND SPRING MO	0.0	16	14	12	12	11
7065500	ALLEY SPRING AT ALLEY MO	0.0	70	62	59	57	55
7066000	JACKS FORK AT EMINENCE, MO	398	126	101	90	82	74
7066500	CURRENT RIVER NEAR EMINENCE, MO	1272	514	424	386	359	333
7067000	CURRENT RIVER AT VAN BUREN, MO	1667	720	605	556	521	485
7067500	BIG SPRING NEAR VAN BUREN MO	100	295	268	257	249	241
7068000	CURRENT RIVER AT DONIPHAN,MO.	2038	1196	1035	966	916	865
7070500	ELEVEN POINT RIVER NEAR THOMASVILLE, MO	361	8.1	5.1	4.2	3.7	3.2
7071000	GREER SPRING AT GREER MO	100	190	144	125	111	98
7071500	ELEVEN POINT RIVER NEAR BARDLEY, MO	793	277	215	190	174	158
7185700	SPRING RIVER AT LARUSSELL, MO.	306	42	31	26	23	20
7186000	SPRING RIVER NEAR WACO, MO	1164	64	35	24	17	12
7186400	CENTER CREEK NEAR CARTERVILLE, MO	232	29	21	17	15	12
7187000	SHOAL CREEK ABOVE JOPLIN, MO	427	83	56	44	35	27
7189000	ELK RIVER NEAR TIFF CITY, MO	872	83	47	31	22	13

GROUNDWATER

Groundwater is a component of the hydrologic cycle, and intimately linked with surface water. All aquifers are dependent on the surface for their source of water. The contributing area is called the recharge area. Water infiltrates the ground either from natural recharge (e.g. precipitation) or from artificial recharge (e.g. impoundments or pumping water back into aquifers). Depletion of groundwater can be in the form of evaporation, transpiration, springs, well pumping or other modes.

The difference between recharge and depletion is expressed by a change in groundwater storage. Any imbalance of the water budget of a groundwater system will result in changes of storage in the aquifer.

From well logs, and other data sources located at the Missouri Department of Natural Resources, Division of Geology and Land Survey, the characteristics of the aquifers underlying an area can generally be determined. Table 4 provides a statewide description of water bearing formations and potential water yields (Vandike 1993).

The state has a network of monitoring wells that record static water levels. This effort is conducted by the Missouri Department of Natural Resources, Division of Geology and Land Survey. Wells are distributed around the state. Periodically, data is published in reports. The last report was “Groundwater Level Data For Missouri Water Year 1991-1992 by James E. Vandike” (Vandike, 1993). This report contained data from 44 wells. Figure 19 and accompanying Table 5 show the locations of the wells, the types of aquifers monitored and the years of data (as of the 1993 report). This data tells us the decline in water levels in the aquifers, as they are affected by depletion (use, natural outflow from evaporation, transpiration, and re-emergence as surface water) or increase in water levels from recharge. Water level data may also be available from public or private well owners that monitor levels.

SPRINGS

Missouri has a great number of springs, especially in the Ozark region. Springs are where water emerges from a groundwater system and becomes a surface water system. Some springs have a very rapid response to precipitation. Others do not show such direct response, and are more dependent on the groundwater system from which the water emerges. From historic data, it is apparent that spring discharge decreases during drought. The lowest discharge on record for Bennett Spring was 55 cfs, recorded on November 13, 1934. The long-term average discharge for November is 160 cfs.

There is very little long-term discharge data available for Missouri springs. Consequently, this limits our ability to perform statistical analysis that could be applied to ungaged springs. By employing methods from both surface and groundwater investigations it would be possible to do yield studies of springs.

Table 4. Generalized section of geologic and hydrologic units.

SYSTEM	SERIES	GROUP	GEOLOGIC UNIT	HYDROGEOLOGIC UNIT
Quaternary	Holocene		Alluvium	Missouri and Mississippi rivers and in Mississippi embayment (southeastern Missouri). 500-2,000 gpm. Yields are less along smaller rivers.
	Pleistocene		Loess, till, and other drift, sand and gravel	Drift and till typically yield 0-5 gpm. Drift-filled preglacial valleys typically yield 50-500 gpm.
Tertiary	(undifferentiated)			Wilcox Group (Mississippi embayment only), 50-400 gpm.
Cretaceous	(undifferentiated)			McNairy Formation (Mississippi embayment only), 200-500 gpm.
Pennsylvanian	(undifferentiated)			Northern Missouri and Osage Plains, 1-20 gpm, regionally forms a confining layer.
Mississippian	Chesterian		(undifferentiated)	Springfield Plateau aquifer
	Meramecian		(undifferentiated)	
	Osagean		Keokuk Limestone Burlington Limestone Grand Falls Formation Reeds Spring Formation Pierson Formation	Southwest, central, and eastern Missouri, 5-30 gpm.
	Kinderhookian	Chouteau Group	Northview Formation Sedalia Formation Compton Limestone	Ozark confining unit
			Hannibal Shale	
Devonian	(undifferentiated)			
Silurian	(undifferentiated)			
Ordovician	Cincinnatian	Maquoketa Group	Orchard Creek Shale Thebes Sandstone	
			Maquoketa Shale Cape Limestone	Ozark aquifer (upper)
	Mohawkian	Decorah Group	Kimmswick Limestone	
		Plattin Group	Decorah Formation Plattin Formation Joachim Dolomite Dutchtown Formation	
			St. Peter Sandstone	Yield is greatest from St. Peter Sandstone. Yields of 5 to 50 gpm are possible.
	Whiterockian		Everton Formation	
	Canadian		Smithville Dolomite Powell Dolomite Cotter Dolomite Jefferson City Dolomite Roubidoux Formation Gasconade Dolomite Gunter Sandstone Member	Ozark aquifer (lower) Yields vary greatly with location and well depth. In Salem Plateau, yields are typically 50-100 gpm. In Springfield Plateau and central Missouri, yields are typically 500 to 1,200 gpm.
Cambrian	Upper Cambrian		Eminence Dolomite	
		Elvins	Potosi Dolomite	
			Derby-Doerun Dolomite Davis Formation	St. Francois confining unit.
			Bonneterre Formation Lamotte Sandstone	St. Francois aquifer. Yields of 10 to 100 gpm are possible.
Precambrian	(undifferentiated)		Igneous, Metasediments, and other metamorphic rock	Not a significant aquifer.

(Modified by Vandike from Vandike, J.E., 1993, Groundwater level data for Missouri, water year 1991-1992, Water Resources Report No. 42: Missouri Department of Natural Resources, Division of Geology and Land Survey.)

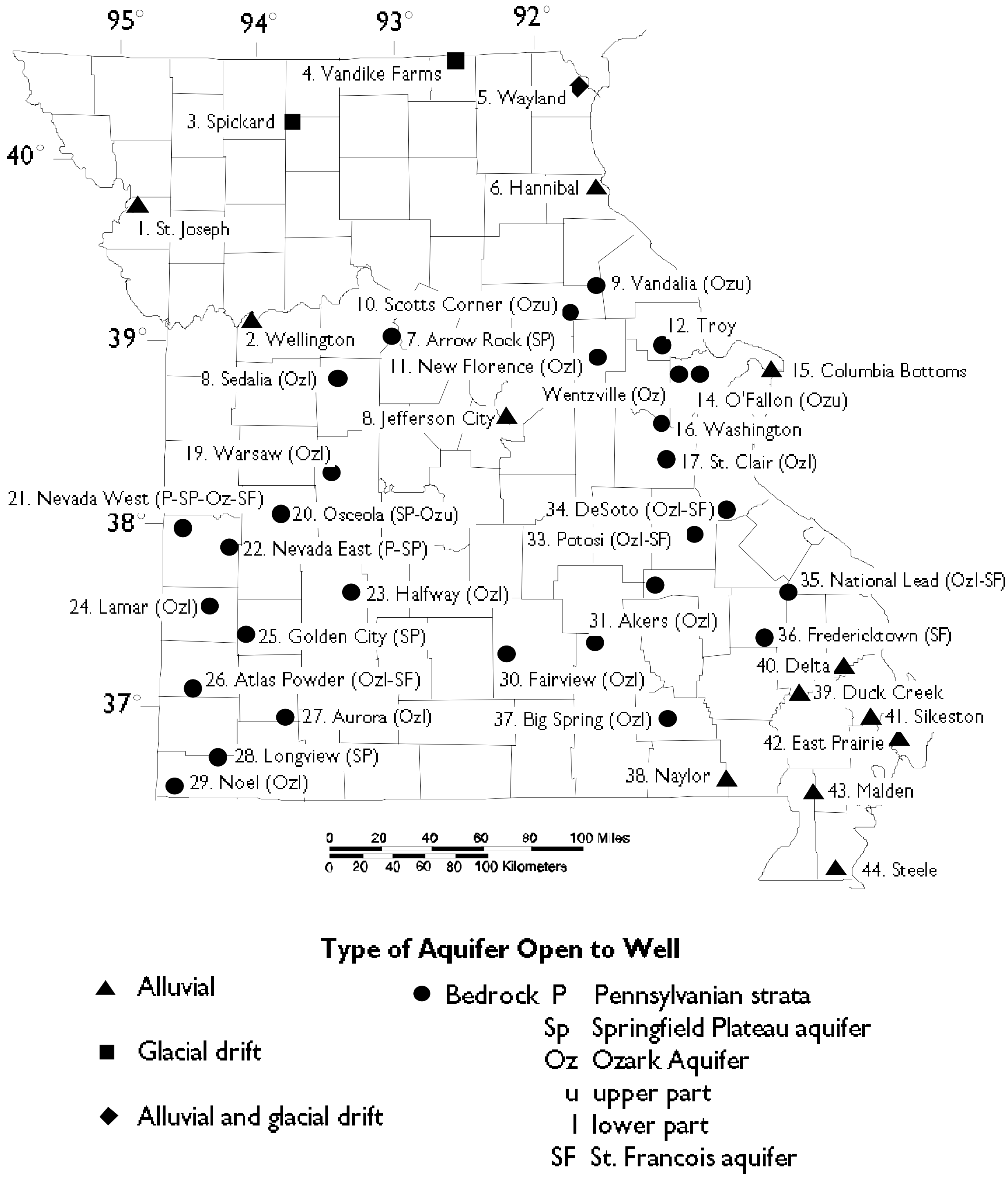


Figure 19. Reference number, well name, location, and producing aquifer for groundwater-level observation wells. (Source: Vandike, J.E., 1993, Groundwater level data for Missouri, water year 1991-1992, Water Resources Report No. 42: Missouri Department of Natural Resources, Division of Geology and Land Survey)

Table 5. Index for groundwater level observation wells

Map number	County	Well name	Years of data
1	Buchanan	St.Joseph	35
2	Lafayette	Wellington	4
3	Grundy	Spickard	34
4	Schuyler	Vandike Farms	12
5	Clark	Wayland	18
6	Marion	Hannibal	35
7	Cooper	Arrow Rock	30
8	Gallaway	Jefferson City	12
9	Audrain	Vandalia	15
10	Audrain	Scotts Corner	11
11	Montgomery	New Florence	11
12	Lincoln	Troy	12
13	St. Charles	Wentzville	12
14	St. Charles	O'Fallon	11
15	St. Louis	Columbia Bottoms	12
16	Franklin	Washington	36
17	Franklin	St.Clair	36
18	Pettis	Sedalia	19
19	Benton	Warsaw	13
20	St.Clair	Osceola	34
21	Vernon	Nevada West	4
22	Vernon	Nevada East	14
23	Polk	Halfway	36
24	Barton	Lamar	24
25	Dade	Golden City	1
26	Jasper	Atlas Powder	36
27	Lawrence	Aurora	4
28	McDonald	Longview	36
29	McDonald	Noel	30
30	Texas	Fairview	36
31	Shannon	Akers	21
32	Iron	Bixby	5
33	Washington	Potosi	4
34	Jefferson	DeSoto	32
35	Perry	National Lead (PH17)	32
36	Madison	Fredericktown	34
37	Carter	Big Spring	12
38	Ripley	Naylor	36
39	Bollinger	Duck Creek	12
40	Cape Giradeau	Delta	36
41	Scott	Sikeston	36
42	Mississippi	East Prairie	36
43	Dunklin	Malden	36
44	Pemiscot	Steele	12

SYSTEM	SERIES	GROUP	GEOLOGIC UNIT	HYDROGEOLOGIC UNIT
Quaternary	Holocene		Alluvium	Missouri and Mississippi rivers and in Mississippi embayment, 500-2000 gpm. Yields are less along smaller rivers.
	Pleistocene		Loess, till, and other drift, sand and gravel	Drift and till typically yield 0-5 gpm. Drift-filled preglacial valleys typically yield 50-500 gpm.
Tertiary	(undifferentiated)			Wilcox Group (Mississippi embayment only), 50-400 gpm.
Cretaceous	(undifferentiated)			McNairy Formation (Mississippi embayment only), 200-500 gpm
Pennsylvanian	(undifferentiated)			Northern and west-central Missouri, 1-20 gpm, regionally forms a confining layer.
Mississippian	Chesterian		(undifferentiated)	
	Meramecian		(undifferentiated)	Springfield Plateau aquifer
	Osagean		Keokuk Limestone Burlington Limestone Grand Falls Formation Reeds Spring Formation Pierson Formation	Southwest, central, and eastern Missouri, 5-30 gpm.
	Kinderhookian	Chouteau	Northview Formation Sedalia Formation Compton Formation	Ozark confining unit
			Hannibal Formation	
Devonian	(undifferentiated)			
Silurian	(undifferentiated)			
Ordovician	Cincinnatian		Orchard Creek Shale Thebes Sandstone Maquoketa Shale Cape Limestone	
	Champlainian		Kimmswick Formation Decorah Formation Plattin Formation Joachim Dolomite Dutchtown Formation St. Peter Sandstone Everton Formation	Ozark aquifer (upper) Yield is greatest from St. Peter Sandstone. Yields of 5 to 50 gpm are possible.
	Canadian		Smithville Formation Powell Dolomite Cotter Dolomite Jefferson City Dolomite Roubidoux Formation Gasconade Dolomite Gunter Sandstone Member	Ozark aquifer (lower) Yields vary greatly with location and well depth. In Salem Plateau, yields are typically 50-500 gpm. In Springfield Plateau and central Missouri, yields are typically 500 to 1200 gpm.
Cambrian	Upper Cambrian		Eminence Dolomite Potosi Dolomite	
		Elvins	Derby-Doerun Dolomite Davis Formation	St. Francois confining unit.
			Bonneterre Formation Lamotte Sandstone	St. Francios aquifer. Yields of 10 to 100 gpm are possible.
Precambrian	(undifferentiated)		Igneous, metasediments, and other metamorphic rock.	Not a significant aquifer

[The stratigraphic nomenclature used in this report is that of the Missouri Department of Natural Resources, Division of Geology and Land Survey modified after Koenig (1961.)]

SYSTEM	SERIES	GROUP	GEOLOGIC UNIT	HYDROGEOLOGIC UNIT
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	Kinderhookian	Chouteau	Northview Formation Sedalia Formation Compton Formation	Ozark confining unit
			Hannibal Formation	
Devonian	(undifferentiated)			
Silurian	(undifferentiated)			
Ordovician	Cincinnatian		Orchard Creek Shale Thebes Sandstone Maquoketa Shale Cape Limestone	
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		Elvins	Derby-Doerun Dolomite Davis Formation	St. Francois confining unit.
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[The stratigraphic nomenclature used in this report is that of the Missouri Department of Natural Resources, Division of Geology and Land Survey modified after Koenig (1961).]

Back Cover: Although it appears to be a scene from a drought, this picture is of sand deposited along the Missouri River by the 1993 flood. These deposits were several feet thick in some places. The State Capitol can be seen in the background. Photo by Nick Decker, DNR.

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